Technologies for Sustainable Energy Development in the Long Term

Proceedings Risø International Energy Conference

Risø National Laboratory, 23 - 25 May 2005

Edited by Leif Sønderberg Petersen and Hans Larsen
The Risø International Energy Conference took place 23 - 25 May 2005 and the aim of the conference was to present and discuss new developments and trends in energy technologies which may make major contributions to sustainable energy developments in the coming decades. The conference addressed R&D related to the individual technologies as well as their integration into the local, regional and global energy systems. The proceedings are prepared from papers presented at the conference and received with corrections, if any, until the final deadline on 15 June 2005.
Contents

Preface 4
Scientific Programme Committee 5
Local Committee 5
Opening Session 6
Session 1 – Energy Development Trends 21
Session 2 – Emerging technologies 44
Session 3 – Hydrogen Economy 75
Session 4 – Hydrogen – Technological Aspects 94
Session 5 – Fuels and Technologies for the Transport Sector 128
Session 6 – Bio-Energy 162
Session 7 – Energy Savings and Efficiency Improvements 196
Session 8 – Fuel Cells 207
Session 9 – Carbon Sequestration and Near Zero Emission 234
Session 10 – Wind Energy 258
Session 11 – Distributed Energy Systems 287
Session 12 – Innovation and Technology Development 308
Session 13 – Emerging and Advanced Energy Technologies 343
Session 14 – Technology Applications in Developing Countries 368
Session 15 – Energy Markets 379
Session 16 – Systems Analysis 413
Session 17 – Resources and Markets in Developing Countries 422
List of participants 457
Preface

The aim of the conference was to present and discuss new developments and trends in energy technologies which may make major contributions to sustainable energy developments in the coming decades. The conference addressed R&D related to the individual technologies as well as their integration into the local, regional and global energy systems.

The world is facing major challenges in providing energy services to meet the future needs of the developed world and, in particular, the growing needs of developing countries. This challenge is enhanced by the need to provide these energy services with due respect to the following factors:

• Economic growth
• Sustainability
• Security of supply

Recent research shows that energy technologies can make significant contributions to economic development while meeting concerns about the climate and environment. However, this will require dedicated policy efforts and intensification of energy research and development.

The Risø International Energy Conference 2005 identified critical areas where action is required now as well as in medium and long-term perspective. The conference focused on scientific development of new technologies, their market perspectives, and realistic contributions to the factors listed above. What are the requirements new technologies need to meet, and what are the perspectives for their role in the future supply system?

The conference also addressed structural changes in the energy sector as well as general policy issues.

The conference focused on:

• Future European and global energy development trends
• Economic and policy issues
• Hydrogen economy
• New and emerging energy technologies
• Carbon sequestration
• Distributed energy systems
• Efficiency improvements and energy savings

The target group

The target group for the conference was researchers, policy makers, energy sector decision makers, funding organisations, ministries, as well as international organisations e.g. EU, IEA, UN.

**Scientific Programme Committee**

- Mogens Arndt, Energi E2, Denmark
- Ib Chorkendorff, Technical University of Denmark
- Jean Claude Van Duysen, European Institute for Energy Research, Germany
- Thomas Flower, Siemens Westinghouse Power Corp., USA
- Abeeku Brew-Hammond, The Schumacher Centre for Technology & Development, United Kingdom
- Robert Feidenhans'l, University of Copenhagen, Denmark
- Jørgen Henningsen, Weatherhead Centre for International Affairs, Cambridge, USA
- Peter Høstgård-Jensen, Elsam A/S, Denmark
- Mike Johnson, CCLRC, Rutherford Appleton Laboratory, United Kingdom
- Jens Kossmann, Stellenbosch University, South Africa
- Hans Larsen, Risø National Laboratory, Denmark (Chairman)
- H. J. Neef, Forschungszentrum Jülich, Germany
- Helge Ørsted Pedersen, Elkraft System, Denmark
- Mark Radka, UNEP, Division of Technology, Industry and Economics, France
- Hans Jørgen Rasmussen, DONG, Denmark
- Ulla Röttger, Amagerforbrænding A/S, Denmark
- Jürgen Schmid, ISET, Germany
- Thorsteinn I. Sigfusson, University of Iceland
- Peter Helmer Steen, Danish Energy Authority, Denmark
- Ulrich Stimming, Technische Universität München, Germany
- Fernando Sanchez, Sudon, Centro Nacional de Energías Renovables (CENER), Spain

**Local Committee**

- John M. Christensen
- Erik Steen Jensen
- Hans Larsen (Chairman)
- Peter Hauge Madsen
- Allan Schrøder Pedersen
- Erik Lundtang Petersen
- Leif Sønderberg Petersen
Opening Session

Chairman: Hans Larsen, Risø National Laboratory, Denmark
MOVING TOWARDS CLEAN AND SECURE ENERGY SYSTEMS

Keynote Address

Professor Jim Skea, Research Director, UK Energy Research Centre, 58 Prince’s Gate Exhibition Road, London SW7 2PG, UK, Tel: +44 207 594 1574, Fax: +44 207 594 1576, Email: jim.skea@ukerc.ac.uk, Web: www.ukerc.ac.uk

INTRODUCTION

Ensuring clean and reliable supplies of energy is acknowledged as an essential policy goal throughout the world. Yet, as energy markets were liberalised during the 1990s, there was a sense in some countries that the energy sector had ceased to have a special character. With oil prices low and the energy mix determined by the pull of market forces, it appeared that energy was a sector like any other without any particular strategic imperatives attaching to it.

Now, with fossil fuel prices high and climate change a pressing political priority, it appears once again that energy in many countries is a “special” sector of the economy, to which a co-ordinated policy approach is required. There are three main reasons why the energy sector can be seen as special:

- energy production and supply is one of the most environmentally damaging forms of economic activity, whether this relates to impacts on the global climate, regional environmental issues such as acid rain, local air pollution or the disposal of wastes.

- breakdowns in the supply and distribution of oil, electricity and other energy carriers can cause enormous social and economic disruption through impacts on transport and power supply.

- no country has ever achieved economic development without using increasing amounts of energy, though energy demand can start to level off when countries reach a certain stage of development.

Against this background, the paper address three issues: a) the nature of the challenge facing energy policy-makers; b) long-term energy developments and technology/policy options; and c) the role of research, development and demonstration (RD&D).

THE “ENERGY POLICY TRIANGLE”

Figure 1 describes the energy policy challenge in terms of a triangle of driving forces. This means of characterising energy policy has been used for some time.

Environmental challenges, as described above, relate to a range of local, regional and global issues. A great deal of attention has been focused on this issue in recent years (e.g. through the Intergovernmental Panel on Climate Change) and this is not explored in any more detail here.
The concept of security of supply is often used loosely to describe a variety of concerns. The two principal concerns relate first to the reliability of networks for transporting, transmitting or distributing energy, especially electricity, and second to the vulnerability to interruptions of supply when economies or sectors are unduly dependent on a limited range of sources. The latter form of insecurity is generally associated with import dependence and geo-political vulnerabilities, though actual losses of supply to final consumers tend more to be associated with reliability issues.

The economic aspects of energy are crucial because, as noted above, no country has ever achieved a high level of economic development without using increasing amounts of energy. Even in developed countries, economic issues are critical. Low energy prices are widely assumed to be attractive because they can contribute to the competitiveness of a country's industry and make energy services (heating, cooling, mobility) affordable to individual citizens. It has become almost axiomatic in many countries that liberalising energy markets to increase economic efficiency and drive out costs is the primary task in the economic management of the energy sector.

Some technologies can be seen as contributing to environmental, security and economic goals simultaneously. Increased energy efficiency and lower cost forms of renewable energy fall into this category. But there can clearly be tensions between the three energy policy goals that policymakers cannot avoid. For example, taxes that discourage the use of polluting fuels may bring environmental benefits while having adverse effects on competitiveness and affordability. Imported energy may be relatively cheap, but excessive dependence may threaten security of supply. The use of indigenous fossil fuels in some countries may have negative environmental consequences.

The “energy policy triangle” can be seen as an enduring way of characterising the interplay between different driving forces in the energy sector. However, the relative priority attached to these driving forces, and the way in which they are resolved, vary from time to time.

For example, following the 1970s oil crises, security of supply and the economic consequences of supply interruptions were a prime concern. Policy efforts in consuming countries focused on reducing oil dependence, even if this meant increasing the use of environmentally challenging fuels such as coal. Local air pollution issues were addressed, but regional environmental problems (e.g. acid rain) received little priority while global climate change had yet to emerge as an issue.

Following the collapse in oil prices in the mid 1980s, interest in the economic aspects of energy supply and demand remained a high priority. But it took a different form, with a growing interest in the liberalisation of energy markets, especially those for electricity. At the same time, climate change began to rise up the environmental agenda. Following the signing of the Climate Convention in Rio de Janeiro in 1992, there began a concerted effort to develop policies to reduce emissions of greenhouse gases from the energy sector. Throughout the 1990s and beyond, security of supply became a issue of lesser concern.

The key question now is whether there will be a further shift in the way in which the three fundamental driving forces are resolved. Greater global insecurity since 9/11, and persistently high oil prices above $40/barrel have now brought energy supply security to the fore. In Europe, there is the additional challenge of declining oil and gas supplies from the North Sea, which will increase import dependence in the coming years. Climate change continues to be identified by many countries as a key policy priority. Both climate change
and supply security demand a strategic response. In addressing economic aspects of the energy sector, the challenge will be to reconcile the strong market framework that has emerged in many countries with a more strategic approach that requires the market to be steered, or even over-ridden.

THE CURRENT ENERGY CHALLENGE

The International Energy Agency (IEA) recently assessed the prospects for world energy demand and supply in its latest World Energy Outlook. The starting point for the analysis is a “business-as-usual” projection of world energy demand, shown in Figure 2. It should be emphasised that this is not a prediction of how world energy demand will develop until 2030. It is a projection of what might happen should governments choose to retain the current set of energy policies and introduce no further measures. In another paper at this conference, the IEA describes an alternative scenario in which governments take further measures to reduce CO2 emissions and reduce import vulnerability. But the “business-as-usual” scenario is useful because it helps to measure the gap between current trends and desired outcomes, pointing to the scale of the policy response that might be required.

The key point from Figure 1 is that both primary energy demand and global CO2 emissions will increase by some 60 per cent between now and 2030 under the business-as-usual” scenario. This contrasts with the oft-cited IPCC suggestion that CO2 emissions might need to be reduced by 60 per cent below current levels by the middle of the century in order to stabilise atmospheric concentrations. Developing countries, whose use of energy is growing rapidly, will account for an increasing proportion of global energy demand. Particular developing countries, notably Brazil, India and China, will play a key role in the international energy system.

Furthermore, in spite of concerns about climate change, fossil fuels will account for an increasing, not a decreasing, proportion of our energy mix. Fossil fuels will account for 85 per cent of additional demand between now and 2030. We will become more, not less, dependent on oil and supplies will become increasingly concentrated in a small number of producer countries, in particular OPEC members located in the Middle East. An increasing proportion of oil use will be accounted for by the transport sector. The vulnerability of consuming countries to oil supply interruptions will therefore grow, representing perhaps the greatest source of insecurity of energy supply.

In general, the “business-as-usual” scenario suggests that, left to itself, the world energy system will evolve in a direction that is contrary to the stated aims of most governments. The key question is whether it is possible to effect the type of turn-round that might be required.

There is a sign that some countries and jurisdictions are beginning to recognise the long-term nature of the challenge and are setting policy goals accordingly. The UK, for example, has set itself the goal of “putting ourselves on a path to cutting CO2 emissions by 60 per cent by 2050”. The EU came close to committing itself to 70-80 per cent reductions over the same timescale. The question, however, is whether the setting of such long-term targets by themselves provide a sufficient steer to energy markets.

Figure 3 provides some evidence as to the change of pace that would be required for the UK to meet its long-term goal, and whether this is compatible with past experience in the energy sector, over a similarly long timescale. The figure shows annual percentage rates of growth for gross domestic product, primary energy demand and energy-related CO2 emissions over five time periods between 1957 and 2003.
The two time periods 1957-73 and 1983-91 are perhaps most representative of long-term energy developments. In each period, primary energy demand grows roughly 1 per cent more slowly than GDP (a “1 per cent de-coupling”), while CO2 emissions grow roughly 1 per cent more slowly than primary energy.

In the other time periods there are however, substantial diversions from the long-term trends. In 1973-83, the relationship between CO2 emissions and energy demand did not change (i.e. CO2 emissions fell faster than primary energy), but the de-coupling between energy and GDP increased to over 2 per cent per annum. This can be attributed to three factors: a) the significant declines in energy-intensive manufacturing industry in the UK over this period; b) market responses to higher energy prices; and c) purposeful policy action in response to the oil crises.

In the period 1991-2000, primary energy use and GDP were once again de-coupled by around 2 per cent per annum, while CO2 emissions were de-coupled from energy by around 1.5 per cent. CO2 emissions fell, while GDP continued to rise at close to 3 per cent per annum. These developments during the 1990s can be attributed almost entirely to the “dash for gas”, where electricity generators invested heavily in efficient, combined cycle gas turbine (CCGT) plant following liberalisation of electricity markets. The efficiency of the stations, plus the low carbon emission factors associated with natural gas, are key explanatory factors.

The period 2000—2003 is perhaps too short to draw any conclusions, but it shows the unfortunate feature of CO2 emissions rising faster than primary energy demand, mainly because electricity generators responded to higher gas prices by increasing production from coal-fired stations. Nevertheless, a historically impressive 2 per cent per annum de-coupling of GDP and primary has been achieved.

These historical trends are compared with what would need to happen under one of four scenarios prepared by the UK’s Royal Commission On Environmental Pollution. These scenarios were intended to show how the UK could cut its CO2 emissions by 60 per cent by 2050. Figure 3 shows that a 4 per cent de-coupling of GDP and CO2 emissions would be required if economic growth were to continue at historic rates. In the scenario illustrated, 3 percent would be accounted for by GDP-energy de-coupling and 1 per cent by CO2-energy de-coupling, but other combinations are possible.

The key points emerging from this comparison of historic trends and future needs are:

- Step-changes in the relationship between GDP, energy use and CO2 emissions have occurred in the past in response to market developments and deliberate policy action.
- These changes tend not to have persisted for any length of time.
- Energy and CO2 appear to have been de-coupled sufficiently to meet the long-term requirements, but this de-coupling has never coincided with the required de-coupling of energy and GDP.
- In the future, growth in energy demand and GDP may need to be de-coupled to unprecedented amounts to achieve the long-term goals.
AVAILABLE MEASURES

The technical measures which could, in principle, bridge the gap between business-as-usual trends and energy policy aspirations are well known. However, specific classes of technology do not necessarily contribute to environmental and security of supply goals in equal measure. Much of this conference is devoted to these options and it is not appropriate to explore these in any detail here.

Measures that could be deployed in the short-term include energy efficiency and renewable energy generation. Technologies within these categories are readily available, though there are significant social, economic and political issues associated with take-up. These include the acceptability of renewable technologies in specific locations and inertia among energy consumers. Efficiency and renewables each contribute to both reduced CO2 emissions and security of supply.

In the medium-term, possible options include nuclear power and carbon capture and storage (CCS) from fossil fuel combustion in large sources such as power stations. There are demonstrated acceptability issues associated with nuclear power, while the acceptability of CCS has not been fully tested. Investment in nuclear power plant is taking place in a number of countries, but in most European countries and in the US there has been no investment for some time. Given planning and construction times, nuclear power can therefore be regarded as a medium term option in many countries, with significant amounts of power beginning to flow only by around 2020, even if a significant political turn-round were to take place. CCS, which has barely reached the demonstration stage outside some existing niche applications, might be deployed on a similar timescale. Nuclear power would contribute to energy security and the reduction CO2 emissions, but there are unresolved issues associated with nuclear waste in a number of countries. CCS would certainly lead to reduced CO2 emissions, but the security implications depend on the sourcing of fossil fuels.

Long-term and more speculative options for the energy sector include fusion power and a shift to the hydrogen economy. A move towards the hydrogen economy could start to break the link between oil and transport. It could also lead to substantial reductions in greenhouse gas emissions if hydrogen could be produced sustainably. Fusion power could, in principle, supply large amounts of energy. However, fusion has yet to be demonstrated on a significant scale and many scientific and engineering problems remain to be resolved. The ITER project could provide that demonstration, but international sensitivities associated with siting have yet to be resolved. The cost of a fusion power plant would be critical.

THE ROLE OF RD&D

The focus of energy RD&D

Research and innovation has a key role to play in addressing these long-term challenges. Policy innovation is required to accelerate the deployment of existing technologies and technological innovation to bring forward advanced technologies. Innovative policy approaches are prompted partly by the increasingly market-oriented approach to energy policy. Novel measures include emissions trading, voluntary agreements, fiscal measures and market transformation/integrated product policy. Traditional regulation continues to have a role. Technological innovation is vital given recent interest in ambitious long-term targets such as the UK’s goal of reducing CO2 emissions by 60 per cent by 2050. The EU has also considered cutting CO2 emissions by 70-80% by 2050.
A recent meeting of G8 and leading developing countries has shown that the drivers for energy RD&D are similar in most countries. However, there are differences in emphasis. Broadly speaking, security of supply and environmental protection are the principal drivers of energy RD&D in developed countries though these may be prioritised differently. In developing countries, poverty alleviation and economic development tend to be the principal drivers.

A core set of energy RD&D priorities is recognised in most countries. Common priorities are, for example: fuel cells; hydrogen; renewables; and the built environment. The focus on specific renewable energy technologies, e.g. wind or biomass, tends to reflect national circumstances and resource endowments.

Nuclear R&D remains a high priority for many countries but the focus depends on policy orientation. In countries that have a policy to phase out nuclear power, research focuses on waste disposal, safety and the decommissioning of reactors. Other countries are investing in research on advanced reactor designs. On the whole, nuclear R&D budgets tend to be higher than non-nuclear budgets.

There is a high level of interest in clean coal research in a number of countries, with carbon capture and storage beginning to take a prominent role. There is little publicly funded R&D in the oil and gas arena, reflecting the large scale efforts expended by the private sector.

**Trends in RD&D Expenditure**

Energy RD&D data is notoriously unreliable and hence definitive conclusions about trends should be treated with caution. Nevertheless, Figure 4 provides evidence of a general decline over time in IEA countries. The notable exception is Japan whose annual expenditure of $3bn has been increasing, making it the world’s largest investor in energy RD&D. The US is not far behind Japan, but its expenditure appears to have levelled off. There has not been significant additional investment in energy RD&D to meet recent challenges, certainly nothing like the increases seen in the 1970s in response to the first oil shock.

To make trends easier to observe, Figure 5 translates the data in Figure 4 into index form, using 1990 as the starting point. This shows the full extent of the decline in energy RD&D in some of the European countries, with Germany and the UK having suffered particularly dramatic falls. The decline in the UK can be attributed partly to the privatisation of some of the national laboratories and the nationally owned electricity and gas companies in the late 1980s and 1990s. Note that Figure 5 does not take account of expenditure under the EU Framework Programmes. This would add significantly to any European total. Figure 5 may exaggerate some of the apparent declines in Europe as RD&D spend has switched to the European level.

Figure 6 shows trends in a selection of non-G7 countries. Increases in RD&D have taken place in countries such as New Zealand, Austria and Finland. In the latter country, the increase is accounted for largely by investment related to industrial energy efficiency. In Denmark and Sweden, expenditure has not varied to the same extent.

Energy RD&D is organised in a variety of ways in different countries. The greatest degree of centralisation is in the US with the Department of Energy and the National Laboratories taking a leading role. Elsewhere, there is a diversity of programmes and funding agencies.
Research may be carried out in universities, research institutes, industry and national laboratories. The mix varies from country to country. Competitive tendering is increasingly becoming the norm across IEA member countries. A notable feature is the lack of integration of transport and energy/environmental research into the energy portfolio.

In many countries, fragmentation of research activity is an increasing concern and there is desire for better coordination and greater industry involvement. There is a need for clear strategies, with roadmaps, milestones and evaluation. Striking a balance between the flexibility associated with competitive tendering and keeping options open and the need for a degree of continuity in research programmes is a difficult question.

A key question is whether greater international collaboration would reduce the overall cost and increase effectiveness of energy RD&D. There is a comprehensive portfolio of IEA Implementing Agreements. While there are no formal barriers to the participation of developing countries in these agreements, there are many practical obstacles relating to funding and the capacity of officials to participate in meetings. Securing greater involvement from developing countries remains a large challenge. One possible way in is through the new, largely US-led, international initiatives that have emerged in recent years. Examples include the International Partnership for the Hydrogen Economy (IPHE) and the Carbon Sequestration Leadership Forum (CSLF). These have secured the involvement of the major developing countries, notably China. Nevertheless, it is clear that there is no appetite for new international structures or organisations for energy RD&D. The challenge is to make the best use of the institutions we already have.

The EU Framework Programmes

The EU Framework Programmes are of critical importance for European energy RD&D. Proposals for R&D Framework Programme VII, covering the period 2007 - 2013, have just been published by the Commission. The nine priority areas are:

- Health;
- food, agriculture and biotechnology;
- information and communication technologies;
- nanosciences, nanotechnologies, materials;
- energy;
- environment (including climate change);
- transport (including aeronautics);
- socio-economic sciences and the humanities; and
- security and space.

Unlike in Framework VI, energy is identified as a separate priority with a proposed budget of €2.9bn over seven years. This represents 6.6% of the total FP VII budget of €44.4bn.

The broad goals set within the energy priority area are to:

- address the pressing challenges of security of supply and climate change, while increasing the competitiveness of Europe’s energy industries;
- transform a fossil-fuel based energy system into a more sustainable one based on a diverse portfolio of energy sources and carriers; and
- enhance energy efficiency.

The proposed energy activities within Framework VII cover:
• hydrogen and fuel cells;
• renewable electricity generation;
• renewable fuel production;
• renewables for heating and cooling;
• CO2 capture and storage technologies for zero emission power generation;
• clean coal technologies;
• smart energy networks;
• energy efficiency and savings; and
• knowledge for energy policy making

Framework VII covers only non-nuclear RD&D. The proposed Euratom budget for the five year period is $3.1bn, of which €2.2bn is for fusion research, $0.4bn for fission and radiation protection, and €0.5bn for the nuclear activities of the JRC. The fission budget covers: radioactive waste management; reactor systems; radiation protection; infrastructures; and human resources and training.

CONCLUSIONS

There is a renewed recognition that energy makes a strategic contribution to social and economic life, both in Europe and in other parts of the world. Innovation, in both the policy and technological domains, is seen to be essential in supporting strategic energy goals, especially in the long-term.

It is clear that a range of technology options is going to be needed in the future. The public sector has an important role to play in RD&D where high risks and uncertain benefits discourage private sector leadership. This is leading to re-appraisals of energy RD&D budgets. There are now signs of a reversal of the decline in energy RD&D funding in some countries. There is a general appreciation of the need to co-ordinate energy RD&D better, for example via the EU technology platforms.

The message for the energy research community is that energy is a key policy concern once again, as is energy RD&D. Rather than battling over budget allocations, the community needs to acknowledge the need to retain a range of technology options and respond to the challenge collectively.
FIGURE 1: THE ENERGY POLICY TRIANGLE

ENVIRONMENT

ECONOMICS

SECURITY
FIGURE 2: PROJECTED WORLD ENERGY DEMAND BY SOURCE

Source: IEA
FIGURE 3: GDP, PRIMARY ENERGY AND CO2 EMISSIONS IN THE UK
FIGURE 4: ENERGY RD&D TRENDS IN G7 COUNTRIES
FIGURE 5: INDEXED TRENDS IN G7 ENERGY RD&D
FIGURE 6: ENERGY RD&D TRENDS IN SOME NON-G7 COUNTRIES
Session 1 – Energy Development Trends

Chairman: Peter Helmer Steen, Danish Energy Authority, Denmark
Long-term global energy developments and their implications for Europe

M.A. Uyterlinde, J.R. Ybema, G.H. Martinus
ECN Policy Studies, the Netherlands

ABSTRACT

In the coming decades, Europe’s energy system is facing a number of challenges. The most pressing ones, mitigation of climate change and dependency on imported fossil fuels represent increasing risks for sustained economic growth and have a worldwide dimension. The strategies for tackling these issues must be designed taking worldwide developments into account. Alternative energy sources and new technologies will have to play a key role. In the analysis of the potential impact of new technologies and the evaluation of policy options, energy - economy - environment (E3) models can provide useful insights. In the EU sixth framework project CASCADE MINTS, twelve E3 models have been used to evaluate possible developments of the world energy system and the implications for Europe. The paper also discusses different strategies to counter these developments, relying on technologies based on renewable energy, nuclear power, CO₂ capture and storage, or hydrogen. All options have their own characteristics, costs, advantages and consequences. Recommendations are given about robust elements of a strategy towards a more sustainable European energy system.

1 Challenges for the future energy system

Recent trends and projected developments indicate that in the coming decades, Europe’s energy system is facing a number of challenges. The energy system is not becoming more sustainable. On the contrary, for several important issues the situation is expected to deteriorate. The key issues are that greenhouse gas emissions are projected to increase and import dependency of fossil fuels will accelerate, increasing the risks related to climate change and energy supply disruptions.

This paper provides information on the severity of issues in case there is no policy intervention. Further, it explores strategies to make Europe’s energy system more sustainable. It gives insight in the options that can contribute to improving future developments, and in how much room is available to intervene via policies and what the consequences of intervention will be.

This paper builds on insights from several energy-economy-environment (E3) models, which have been used to evaluate possible developments of the world energy system and the implications for Europe. E3 models can provide useful insights in the analysis of the potential impact of new technologies and the evaluation of possible policy options. In addition this paper uses experiences from analysis of policies to reduce greenhouse gas emissions and policies to accelerate innovation in the energy system.
2 Key drivers and business as usual scenarios

2.1 Key drivers for future energy use

The main drivers for future developments in the energy system are:

- Population growth
- Economic growth and changes in economic structure
- Existing capital stock: infrastructure, buildings, power plants
- Availability and prices fossil fuels
- Technological change
- Lifestyle and behaviour
- Policy (energy, innovation, fiscal, mobility, environmental)
- Institutional framework
- Incidents
- Climate change

The single driver that potentially can have the largest effect on long-term energy use is technological change. Of course technological change does not occur autonomously. Among others technological change is influenced by economic growth, energy and innovation policy and prices of fossil fuels.

Figure 1 shows schematically the move from the current energy situation towards future energy situations and the influencing factors.

Figure 1: Schematic overview of the key influencing factors on the development towards the future energy system.
While this development is determined by the actions of many actors, such as industries, energy companies etc., there are several drivers that trigger changes. In addition decisions of these actors are influenced by policy objectives. To a smaller or lesser extent they will utilise the potential that energy technologies offer. E3 models have been designed to analyse these kinds of developments.

### 2.2 Insights from business as usual scenario

In the Cascade-Mints project, twelve of these E3 models have been used to evaluate possible developments of the world energy system and the implications for Europe. The business as usual scenario provides information to policy makers, based on a consensus among modellers, on possible developments in a world with moderate GDP and population growth, with no additional policies in place.

**A continuing worldwide reliance on fossil fuels**

World primary energy consumption is expected to more than double in 2000-2050. This is a consequence of the assumptions regarding moderate economic and population growth, implying that a larger growth would also be possible. In line with the assumptions, Asia grows fastest, and quadruples its energy consumption by 2050.

![Figure 2: Development of primary energy consumption by regions](image)

All models indicate that fossil fuels are expected to remain dominant in the world fuel mix by supplying 65-80% of primary energy use (Figure 3). Combined with the growth in primary energy consumption, this will result in an even faster depletion of the global natural resources than today. Although Europe’s primary energy consumption shows a much slower growth than the world average - some 20% until 2030 -its reliance on fossil fuels (70-75% of the primary energy mix, depending on the model), is comparable to the rest of the world.

---

1 The models involved are: Primes, Prometheus, Markal, Message, Poles, GMM, Pace, Times-ee, Newage-w, Nemesis, Nems and DNE21+. Their coverage ranges from world models to individual regions, and their methodology includes energy system (optimisation) models, energy sector simulation models, CGE and and macro-economic models.
Although the models show a consistent picture of the share of fossil and non-fossil fuels in future primary energy mix, they deviate on the contributions of individual fuels. In Europe, particularly the prospects of solid fuels and nuclear energy differ, due to different assumptions on technological development and costs. Coal consumption is expected to stabilise or grow. Some models expect nuclear energy to be phased out, due to high investment costs. There is a certain consensus on Europe’s consumption of natural gas for power production, which is expected to increase significantly, and on the moderately increasing consumption of oil, mainly in the transport sector.

**Security of supply becomes a key issue**

Given the continuing global reliance on fossil fuels, an important issue in the years to come will be the increasing dependence on oil from the Middle East. Although the models show different projections of the evolvement of oil production, they agree that the contribution from the Middle East region grows, and becomes substantially larger. Given the large uncertainty on future oil price developments, confirmed by one of the models indicating that there is a substantial probability of sudden increases in the oil price, this may lead to increased concerns about the security of oil supply on the longer term, particularly in view of the present uncertain political situation in the Middle East.

For Europe, trends are in line with the global developments. Europe’s oil consumption is expected to stabilise at about a third of its primary energy consumption in 2030. Domestic production however is expected to decrease due to limited reserves and high production costs, thereby introducing a greater reliance on imports up to 85% (Figure 4).

For natural gas, Europe’s external dependency will also grow in the next decades. A continuing growth in gas consumption combined with a decrease of gas production in the UK, the Netherlands and Norway, will lead to a higher share of imports from the two main suppliers Russia and Algeria.
The baseline projections show that Europe will encounter more competition on increasingly scarce fossil resources. Given the prospect that other world regions will also increasingly rely on oil from this region, this may indeed lead to further oil price increases, which will affect all economic sectors.

**Worldwide a doubling in CO$_2$ emissions in 2030 compared to 1990**

Overall, the CO$_2$ emissions in 2030 are expected to be approximately twice the level of 1990, the base year of the Kyoto protocol. The largest growth of these emissions is expected to occur in the developing world, in particular in Asia.

In Europe, CO$_2$ emissions grow moderately, when compared to trends at world level. Still, Western Europe is not on track towards the targets agreed under the Kyoto Protocol. The carbon tax of 10 euro/(ton CO$_2$), included from 2012 onwards to reflect the assumption that some type of climate policies will be implemented, does not suffice to curb the growing trend in CO$_2$ emissions.

3 The role of more sustainable options in mitigation scenarios

Several studies have indicated that a 60-80% reduction of GHG emissions in 2050 is required for regions like the EU to limit the risks from climate change. The main technical options to reduce emissions of CO$_2$ emissions include energy efficiency, substitution towards low carbon technologies (renewables, nuclear, natural gas) and CO$_2$ capture and storage. Besides, non-technical options exist to reduce demand for energy. As these options also affect security of supply, such effects need to be covered when designing mitigation strategies. These options are briefly introduced below.

---

2 It is noted that this paper is not covering all options to improve long-term security of supply measures; e.g. diversification of natural gas supplies, storage of natural gas and substitution to conventional use of coal are not included.
3.1 Energy efficiency

Energy efficiency improvement involves the continuous process of adopting technologies that are more important than their predecessors and non-technical measures that reduce energy use. Currently the rate of efficiency improvement is about 1% per year in many EU countries. The current rate is lower than in the 80’s and 90’s. Availability of efficient energy technologies, high energy prices, a fast rate of turnover of capital in the energy sector and incentives from energy efficiency policy all have positive effects on the rate of energy efficiency improvement.

Further improving energy efficiency is a robust element in all strategies to mitigate greenhouse gas emissions or to increase security of supply. There is potential to significantly accelerate the rate of efficiency improvement. Many studies assign the largest potential for CO$_2$ emission reduction to energy efficiency. While the focus is still on technical improvements, there is also a significant potential for energy efficiency improvement by non-technical measures e.g. through improved logistics, to reduce transport demand, improved product design and recycling, to reduce material use.

The challenge is to design effective strategies to utilize this potential. This requires balanced strategies involving among others R&D incentives, to develop new generations of even more efficient technologies, subsidies for manufacturers of such technologies and for early adopters and regulation to stop the use of outdated inefficient technologies. E3 models usually have little detail on energy efficiency measures. Detailed simulation models of sectoral energy use appear more useful to gain detailed insights.

3.2 Renewables

Renewables are indigenous and CO$_2$ neutral, and therefore can contribute to diversification of the fuel mix, and avoid greenhouse gas emissions. However these technologies still face financial and other barriers, and will have to be stimulated ‘down the learning curve’.

Although the models show differences in their projections on which technologies will be necessary to achieve a 20% target in 2020 for Europe, they agree that 40%-50% of the primary renewable supply is based on biomass, and 20-25% comes from wind energy. Figure 4 illustrates that one of the models projects a substantial share of solar energy, largely due to the implementation of solar thermal water heaters. Although the share of hydropower is also significant, the potential for growth is limited to small installations. Therefore wind energy and biomass will be the strategic options for achieving Europe’s renewables targets towards 2020. Beyond that date, other options such as PV, solar thermal electricity, wave and tidal energy may show more penetration as well.

Biomass can be applied in different sectors, particularly for power generation and in the transport sector, but also heating and cogeneration. The prospects by sector differ by model, depending whether a generic target is set for all renewables, whether specific policies targeted at different sectors are implemented and depending on the competition from other options for CO$_2$ reduction. A large penetration of biofuels in the transport sector is only achieved under targeted policies such as taxation of conventional transport fuels, because applications in the power sector seem more cost effective. It is noted that the penetration of biofuels has a direct impact on the import dependency for oil, and on CO$_2$ emissions from transportation, which makes the promotion of biofuels a strategic choice for Europe.
3.3 Nuclear energy

Nuclear power currently accounts for approximately one-third of the electricity generating capacity in the EU and is therefore a main topic in the current debate concerning security of energy supplies in the EU and the reduction of GHG emissions. Many nuclear power plants are nearing their technical lifetime. Replacement of existing nuclear power plants by fossil fired plants would put even more stress on both policy issues. Important issues which will shape the future trends in the nuclear sector, are the problems of managing nuclear waste, the economic viability of the new generation of nuclear power plants, the safety of reactors, in particular in Candidate Countries and the policies to combat climate change and improve the security of supply.

Model analyses have shown that nuclear energy could be an important component of carbon mitigation strategies, if the risks due to the safety and high investment costs are not a critical barrier in a liberalised electricity market. With the assumption that carbon prices reach a level of 100 euro/ton CO₂ in 2030, nuclear power plants are one option to reduce the import dependency of natural gas, and could contribute to up to 50% of Western Europe’s power generation mix. However, this would increase the amount of waste with a factor 6 compared to the level in the year 2000. Future risk of nuclear power incidents would depend on the type of reactors that would be built. Nuclear power could serve as a transition technology, because it can postpone the need for investment in other similar capital intensive, low carbon technologies such as CO₂ capture and sequestration (CCS) or renewables.
On the other hand, the analyses have also shown that a nuclear phase out in Europe is feasible, even in a future with a strong climate policy. However, in this case, renewables, natural gas and advanced coal-fired plants with CCS are key options. Consequently, the dependency on natural gas imports would increase.

### 3.4 CO₂ capture and storage

**CO₂ capture and storage (CCS)** is a relatively new technology option. It allows for continued use of fossil fuels while reducing emissions by 80 or 90%, compared to the same installations without CO₂ capture. The main application of CCS is for electricity production. There are also certain opportunities in manufacturing industry and in fuel processing.

CCS will come with an additional cost to any power generation plant. This is true both for the conversion to electricity and the conversion to hydrogen, if hydrogen is used as an energy carrier. CCS will therefore only be applied if future specific or general policies provide the necessary financial incentive.

Model analyses show that CCS can play a key role in cutting CO₂ emissions. In case CO₂ policies are introduced, coal in combination with CCS could be used for hydrogen production. However, the prospects of such developments depend on the availability of low-cost fuel cell vehicles and an adequate hydrogen infrastructure.

### 3.5 Hydrogen and electrification

Recently the transition towards a *hydrogen economy* receives increasing attention from the car manufacturing industry. If hydrogen can be produced with low CO₂ emissions it can contribute to CO₂ reduction. Converting to a hydrogen economy would require a series of transitions: first, a transition when both conventional fuels and hydrogen will be available, and used, for example, in the same internal combustion engine, and second, when hydrogen alone will be used. Model analyses usually show that hydrogen can play a role in CO₂ mitigation scenarios, but probably only at a high cost. Besides, energy efficiency improvements in internal combustion engines and biofuels form strong competitors for use in the transport sector.

Similar, electrification, the substitution from gaseous and liquid fuels to electricity, can lead to significant CO₂ reduction. Use of electric heatpumps and electric vehicles can lead to significant emission reduction if the required electricity is produced with low CO₂ emissions. An advantage of electricity over hydrogen is the high end-use efficiency. Model analyses provide different views on the contribution of electrification as it depends on the yet uncertain availability of electricity sources that are near to CO₂ free.

### 4 Policy instruments

There is potential for significant reduction of CO₂ emissions from Europe’s energy system. As there is no “silver bullet”, a strategy to mitigate CO₂ emissions and/or to improve security of energy supply will involve accelerated deployment of several mitigation options. While renewables, energy efficiency or nuclear energy all hold promise for a CO₂ free future, the overall modeling results suggest that there is not a single strategy that can solve the CO₂ problem.
Given the large inertia in the energy system, short-term action is needed to foster the introduction of advanced and cleaner technologies, in order to enable these technologies to play a significant role in the long term.

Current climate policy can be characterized as “optimisation of the current system”. However, system optimisation is not sufficient to yield drastic CO₂ reduction. This requires system level changes, new roles for governments, companies and citizens, and need to look beyond the current energy system. A transition process including system innovation and societal change is required. Mechanisms involving both demand pull and technology push will be important and need to be managed. A transition towards a more sustainable energy system requires a balanced package of policies and measures, see Figure 5. R&D is needed to develop new options, subsidies and grants are needed to create the initial market for new options and further taxation, emission trading systems and/or regulation are needed to foster further market development. In order to increase participation by industry there needs to be a clear perspective that such packages of policies and measures will materialize and will be sustained over time.

It also requires active involvement of relevant stakeholders. It is the role for governments to create favourable and stable “regime” for companies to invest in innovation. The role for industry and the energy sector is to actively invest in such technologies.

Figure 5: Stimulating the market share of innovative energy technologies requires a mix of policies and instruments, tailor-made to their market status

5 Summary and conclusions

Energy projections indicate that over the coming decades the world and the EU will be confronted with large challenges related to the security of energy supply and climate change. Energy related CO₂ emissions from the EU are projected to slightly increase, while a 60-80% reduction of emissions by 2050 is needed to limit the risks from climate change. Further, Europe becomes increasingly dependent on imports of oil and natural gas.

The main technical options to reduce emissions of CO₂ emissions include energy efficiency, substitution towards low carbon technologies (renewables, nuclear, natural gas) and CO₂ capture and storage. These options need to be combined to realize sizable mitigation. The future role of several options partly depends on the cost and potentials of
other options to mitigate GHG emissions. It depends also on the need for emission reduction. Every option has its particular characteristics. Most options are also advantageous to reduce supply security risks.

Additional policies and measures are needed for realising drastic reduction. Strategies with balanced and tailor-made combinations of R&D, voluntary agreements, regulation and financial instruments are needed, if ambitious environmental policy targets are aimed for. It is expected that this will require new ways of collaboration between governments and companies.

Acknowledgements

The CASCADE MINTS project is funded by the EU under the Scientific Support to Policies priority of the Sixth RTD Framework Programme. The following partners are involved in Part 2 of the Cascade Mints project: ECN (Netherlands), ICSS/NTUA - E3MLAB (Greece); IIASA (Austria), IPTS-Joint Research Centre, (Spain), PSI (Switzerland), ZEW (Germany), IER (Germany), ERASME -University of Paris (France); International Energy Agency, U.S. DOE/EIA (USA), RITE (Japan), NIES (Japan) and Natural Resources Canada (Canada).

References


European Sustainable Electricity; Comprehensive Analysis of Future Demand and Generation of European Electricity and its Security of Supply

William D'haeseleer & Lieve Helsen
University of Leuven Energy Institute (K.U.Leuven)
c/o Applied Mechanics & Energy Conversion
Celestijnenlaan 300A, B-3001 Leuven (Heverlee), Belgium
william.dhaeseleer@mech.kuleuven.be; lieve.helsen@mech.kuleuven.be

Abstract

The paper elaborates on the methodology applied for a Europe wide study, EU-SUSTEL, which aims at providing a fully consistent framework for a secure electricity provision, that is at the same time environmentally friendly and affordable. The conclusions of the study will result in policy recommendations for the EU Member States and the European Commission. The methodology used mixes two 'directions' of analysis. In a first (horizontal) one, the existing electricity systems of the 25 EU countries are analyzed and national policy choices and future projections are studied. Here, we try to understand the logic behind the different electricity-system configurations in the different countries, how these depend on the choices and hypotheses made by the countries and how the individual choices affect the neighbors and the whole EU. Next, vertically then, a subject-wise treatment is considered, whereby both the demand side and the supply-side technologies, including system integration are treated. Concerning the demand side, the link between demand for energy services and the actual electricity demand is studied; on the supply side, all known technologies are considered, up to and including fuel cells, hydrogen, and a variety of perhaps speculative electricity-supply routes. Furthermore, the regulatory and liberalized market framework for an integrated European electricity market is carefully examined and appraised. Based on these analyses, in a combined approach it is then attempted to summarize the 'static' overall social cost (private cost plus external cost) for electricity provision. Subsequently, these cost figures are used as input in carefully screened simulation models in order to perform some well-defined and contrasting scenarios, but in line with the regulatory framework of the energy market. From these results, it must be possible to obtain the 'most-optimal solution' (from an economic-effectiveness point of view—including environmental burdens) for the electricity provision in Europe.

1 Introduction

1.1 General Objectives of the Study

This paper describes the methodology of the FP-6 project study EU-SUSTEL, presently being performed for the European Commission DG Research. The full title of the project reads “Sustainable Electricity; Comprehensive analysis of future European demand and generation of electricity and its security of supply”.

The strategic objective of the study can be summarized as follows. The study is to provide the European Commission and the EU Member States with coherent guidelines and recommendations to optimize the future nature of electricity provision and the electricity generation mix in Europe so as to guarantee an affordable, clean and reliable, i.e., ‘sustainable’, electricity supply system.
In a sense, the aim is to establish a common European methodology to evaluate the ‘sustainability’ (in terms of cost, environmental impact and security of supply) of future electricity provision systems. The implementation of a particular electricity-provision system in the different Member States can take into account different policy preferences and geographic realities, but the overall social cost (including all kinds of externalities) of the chosen system should be computable following the same methodology. Clearly, the consequences of particular choices by some Member States on other Member States should be clearly identifiable.

In summary, there is no problem with a mosaic of electricity-supply systems in the EU, but the consequences of possible non-coherence should be clearly understood in terms of GHG emissions, security of supply, electricity generation and transmission capacity, back-up costs, etc. The resulting picture should furthermore be compatible with an integrated liberalized European market for electricity (and gas). Without compromising the ‘visionary’ projections of this work, throughout the project, the degree of realism is continually checked by the electric industry. The guidelines provided by this project will allow the Commission to help steer national energy policies if that is desirable.

1.2 Current Situation and Approach of this Study

To a large extent, a considerable part of the study consists of a major critical review and evaluation exercise of existing studies, published papers, reports, policy documents, scenarios, etc., whereby those are held against the light of coherence, the expertise and experience of the participating scientists and engineers, and electric industry. Indeed, much has been published over the last years on the energy issue in general and electricity provision in particular, but regrettably, very few critical reviews of the published material have been undertaken. Often, there is plenty of inconsistency of the material published within a particular country, let alone that the material is consistent for whole regions. Assuming that the presentation of the data is not manipulated, the discrepancy often lies in the definitions and conventions behind the numbers. Even stronger, for future projections, many (often hidden) boundary conditions and hypotheses are imposed and assumed, which then lead to a variety of conclusions that may lead to very unrealistic scenarios, mostly insufficiently checked with regard to full consistency. In addition, policy documents often have a style of good intentions, usually wrapped in some diplomatic language, that may reflect a short-sided approach or project nice-looking visions, which may turn out to be very ‘undesirable’ in the long run. By means of an extensive “reviewing exercise”, complemented with own insights, this study intends to “set the record straight” and to deliver a fully consistent picture of future electricity provision.

Putting it simple, the “reviewing and analysis part” serves two purposes. First, this exercise will provide information on the new energy-conversion technologies, both on the demand side and the supply side. As such, taking into account the technical, environmental and economic characteristics, this part of the exercise will provide a well-verified database for the simulation codes that will be used in a later part of the exercise. Second, the variety of simulation codes for modeling the European energy economy, will be scrutinized thoroughly, in order to identify the best suited code(s). As part of that exercise, the existing technological database of the codes will be compared with the results of the technological exercise, discussed above. In addition, existing and published scenarios performed with those simulation codes will be reviewed, analyzed and evaluated.

The “synthesis part” of the study then consists of the development of own scenarios, performed with the best-suited code based using the most appropriate technological database. Clearly, also these scenarios will be compared with existing scenarios performed with other codes.

As a prerequisite to the scenario work, a succinct analysis of the current situation of the liberalized electricity market will be performed with the goal to identify the shortcomings. As an outflow of this exercise, clear boundary conditions compatible with the liberalized markets will be defined.
In order to have a complete view of the variety of electricity-generation technologies and accompanying fuel mix, as well as on the different energy-policy approaches in all the EU member states, a preliminary country-wise analysis will be performed. Indeed, one has to start from the reality of different electricity-system configurations and the ‘behavior’ of population and government (e.g., with respect to economic structure —heavy industry versus service oriented—, attitude on energy efficiency, support schemes for renewables and CHP, stand on nuclear energy, etc) to be able to interpret the European mosaic correctly, to draw conclusions on it and to try to optimize the overall EU electricity provision.

2 Systematic Delineation of the EU-SUSTEL Study

2.1 Overview and General Description

The EU-SUSTEL study will be performed by a group of high-level energy scientists, supported by their laboratories or research groups, in close collaboration with the electric industry.

The scientists have been chosen to guarantee a well-covered geographical representation in Europe, on the one hand, and to draw on their energy-related expertise in their own country and internationally. It has been tried to gather a group of scientists who will rely on rational reasoning and common sense, rather than to choose a-priory ‘ideologically-colored’ advocates of a particular energy vision. Nevertheless, it may be the case that the group covers a variety of insights, approaches and viewpoints, reflecting the differing existing policy orientations in Europe. The combination of the rational approach, but with perhaps different ‘beliefs’ with regard to future technology breakthroughs and public acceptance of particular technologies, may be a guarantee for a well-balanced outcome of the exercise.

The list of participating Scientists is provided under the Acknowledgement Section of the paper, below.

To help guarantee that the views of the scientists are not too different from what real life shows, intensive interaction with electric industry, especially via its umbrella organization, Eurelectric, is planned. Hereby, Eurelectric acts in this study as a ‘Special-Focus Industrial Advisor’. To hear the voice of other major stakeholders, a Consultative Committee, has been established.

As already mentioned above, the work for this study entails a major effort of reviewing and evaluating existing studies and publications, carefully complemented with the participants’ own expertise and views. This review and evaluation must be undertaken with regard to studies referring to countries or regions, as well as with regard to the state of the art, the future projections and the likelihood of penetration and/or renaissance of particular energy-conversion technologies (both on the end-use side as on the supply side). Furthermore, the study must take into account policy trends such as the drive towards a liberalized and fully integrated European electricity (and gas) market, the consequence of climate-change-abatement measures and the promotion of renewable sources and Combined Heat and Power (CHP).

The review and evaluation exercise will consist of a major effort of sifting through the documents, verifying and crosschecking the results and conclusions and of confronting the different viewpoints so as to try to detect the underlying assumptions and boundary conditions. The review performed by one particular project partner will effectively be ‘verified’ as the whole group gets a chance to comment on the conclusions of the reviews. It is the goal that the whole group reaches a consensus on the treated subjects. As mentioned above, the results will be reviewed by the ‘Special-Focus Industrial Advisor’, Eurelectric, and will be discussed with the Consultative Committee.

After all technology-related and country-oriented reviews have been finished and a consensus on the technical, economic and environmental data of the technologies and their evolution, and their
degree of implantation in particular countries has been reached, a limited number of well defined scenario runs will be performed with the code(s) chosen from an analysis exercise of simulation codes. The boundary conditions and hypotheses of these scenarios will to a large extent be determined by the so-called context issues such as liberalized markets, climate change and other specific policy trends (such as renewables, CHP, energy efficiency, etc).

The work will deal with the entire EU, i.e., the EU-25. Because of expected difficulties with the availability of ‘good’ documentation on the most recently acceded 10 member states, some analysis may be more detailed for the EU-15 than for the EU-25.

To be clear, little original research is expected from this study. The emphasis lies on consistency of data, approaches and policies. Hopefully some new insights might emerge, both from the country and technology reviews, and from the scenario runs, but they will perhaps be more of a global methodology-related nature than having a novel and innovative character.

2.2 Country-Wise Analysis for EU-25

The first type of tasks is situated in the ‘horizontal’ direction. It concerns a review about the energy-related documents of countries or groups of countries. The aim is to identify the current ‘weak points’ (if any) in the European electricity generation mix and electricity provision system with respect to cost, environmental impact and security of supply. Through a review exercise of existing electricity generation technologies, the overall integrated generation systems and their interconnections (for electricity and gas) in the European countries, it will be evaluated what are the environmental effects, the global cost and the reliability of each electricity supply system. In addition, the future electricity provision, as envisaged in policy documents of the member states (if available), will be carefully looked at and commented upon.

Practically speaking, the idea is that a partner belonging to a particular country (or familiar with it) thoroughly reviews the appropriate ‘relevant’ documents dealing with the electricity-related energy policy of that country. One should start from international reviews such as the tri-annual IEA reviews per country [1] (if they exist for the country in question). Next, typical European reports, dealing with the different countries (such as ‘Annual Energy Review’ [2], ‘European Union Energy Outlook to 2020’ – Nov 1999-[3], European Energy to 2020’ – Spring 1996 [4], ‘European Energy and Transport; Trends to 2030’ – January 2003 [5]). Then, appropriate other international reports dealing with that country should be consulted, after which all ‘relevant’ national reports should be studied in detail. As examples for these last ones, we mention –non exhaustively– the reports issued by generators, utilities, federations, etc and reports such as ‘Analysis of the Means for the Production of Electricity and the Re-orientation of the Energy vectors’ (AMPERE) in Belgium [6], the governmental white paper in the UK ‘Our Energy Future: Creating a Low-Carbon Economy’ [7] and the reaction to it by a.o. Laughton ‘Power to the people: Future-proofing the security of UK power supplies’ [8], the French white paper ‘Livre blanc sur les énergies’, resulting from ‘Le débat national sur les énergies’[9]. For the newly acceded countries, a good starting point is the Commission’s memo ‘Enlargement and European Union Energy Policy’ [10]. Also, the information of Ref [5] will be highly relevant in that respect, as will be the documentation on ‘Trans European Energy Networks’ [11].

The reviews are to take into account the different policy orientations in different countries (e.g., the nuclear option in France and the wind option in Denmark) but should not consider these policies as being frozen. Political reality demands that flexible policy options are kept open; but the reviewers should certainly indicate the degrees of freedom for ‘policy freewheeling’.

---

1 The distribution of work is as follows. BeNeLux: partner from BE; Germany & Austria: partner from DE; Finland: partner from FI; Greece: partner from EL; Sweden: partner from SE; Italy: partner from IT; UK & Ireland: partner from UK; France: partner from FR; Spain & Portugal: partner from ES; Denmark: partner from DK; Baltic States: partner from FI; Cyprus & Malta: partner from EL; Hungary, Poland, Slovakia, Slovenia and Czech Republic: partners from EL, BE and DE.
A critical analysis should result, whereby the reviewers do not necessarily have to ‘agree’ with the conclusions of official documents. The review and evaluation by the (home) partner will be scrutinized by the project management and can be checked by a different partner, if so desired. The conclusions of these (initial) reviews are to be written down in a limited-size report with clear explanatory and justifying statements. In addition, a permanent review and the making available of information (especially on the new member states) will be done by the ‘Special-Focus Industrial Advisor’ Eurelectric.

2.3 Anticipation of future electricity demand

Under this heading, the objective is to make projections for reasonable evolution of demand for energy services and to determine the relationship with electricity demand. Furthermore, justified Demand Side Management (DSM) measures should be proposed.

On the future demand for electricity, a careful analysis is needed. Before considering the electricity supply side, it is necessary to evaluate possible electricity consumption evolutions in the future. To study the evolution of electricity consumption, one must first establish the ‘desirability’ to reduce electricity demand. In fact, one can only guess the need for energy services. Economic growth and demand for energy services are usually strongly related. But the electricity demand does not necessarily show the same trend. The required electricity demand follows from things such as the efficiency and the cost of end-use technologies, exchange between energy carriers (depending on the price of electricity versus other energy carriers), etc. Comparison of the total cost of a saved kWh versus a supplied one, should clarify whether electricity reductions should be exogenously encouraged or whether the market should be allowed to determine the growth of electricity demand. This issue is not trivial and is characterized by a fierce debate between the ‘conservationists’ (Lovins, Geller and others) and the ‘classical economists’ (Joskow, Sutherland and others). Furthermore, shifts between energy carriers may lead to less desirable effects, for environment, flexibility of use, etc. Based on the outcome of the demand issue, appropriate DSM measures should be proposed to manage a justified evolution of the electricity demand in the different countries.

Given that encouraging stimuli are desirable to reduce the demand for electricity, it is important to figure out precisely what is meant by the so-called energy-savings potentials. Top-down considerations will have to be confronted with bottom-up approaches (based on end-use technologies) to determine the technical, economic and market potentials. Furthermore, it is important to find out appropriate measures (that do not distort the markets and therefore do not lead to undesirable feedback effects) that should be used to manage a justified evolution of the electricity demand.

The following aspects need therefore be studied to obtain a good grasp of the future demand of electricity:

1. Economic evolution of the European Union (as part of a world-wide economy), primary energy provision and ‘projected’ fuel prices;
2. Evolution of demand for energy services and the influence on electricity demand;
3. Possibilities for rational use of electricity, energy efficiency of end-use technologies and demand side management to dampen the demand for electricity.

2.4 Electricity Generation Technologies and System Integration

New supply-side conversion technologies will be necessary in the future. A detailed analysis of the current electricity-generation technologies and a projection of the evolutionary improvements
is to be undertaken. The whole range of centralized and decentralized technologies will be considered. For each technology, a realistic range of technical, environmental and economic characterizing parameters are to be identified and future evolutions are to be estimated, with a horizon of 2030-2050.

Four extra items are considered: electricity storage, the possibilities of fuel cells including the reasonableness of a future hydrogen economy, CO\textsubscript{2} capture and storage, and the possibilities for unconventional, speculative and bifurcation-causing technologies. All of these aspects must be critically evaluated.

The following items are being studied.

1 Fossil-based electricity generation technologies:
   a. Coal fired technologies
   b. Oil & gas fired technologies
   c. Combined heat and power
   d. CO\textsubscript{2} capture and storage

2 Nuclear electricity generation
   a. Nuclear fission
   b. Nuclear fusion (limited scope)

3 Renewable flows & ‘alternative’ technologies & carriers
   a. Wind power
   b. Photo-Voltaic conversion
   c. Biomass applications (including waste)
   d. Hydro power
   e. Geothermal conversion
   f. Fuel cells
   g. Hydrogen economy
   h. Electricity storage
   i. Less-conventional and speculative forms of renewables (ocean currents, space solar, other)

4 System integration
   a. Integration of centralized and decentralized generation; influence on the grid
   b. Greenhouse-gas emissions due to interaction of centralized and decentralized generation (because of operation-time effects and investment consequences)

Most of these subjects are self explanatory, although some comments are in order on the aspect of ‘system integration’.

The grid-related system integration at this stage only concentrates on the technical integration of decentralized and centralized generation, with respect to the electric grid. At this level, it is treated in general; geographic international bottlenecks are not yet considered. These will be dealt with in a later Section, where the aspects of the liberalization (including cross-border transmission capacity and congestion) are considered. This Section also pays attention to the appropriate infrastructure for gas supply for decentralized and centralized generation, and possible conflicts with heating requirements in dwellings. The issue of storable-fuel requirements is contemplated here. As to environmental effects, the interaction of centralized and decentralized generation leads to non-trivial effects because limited operation times of some decentralized generation (such as CHP) together with postponement of investments in centralized generation, may lead to higher than expected emissions.

2.5 Regulatory Framework of Energy Markets

In order to paint a realistic picture of the future electricity provision, it is therefore imperative to make an analysis of the current regulatory framework and its technical and economic consequences concerning the liberalization of the electricity market (and the influence of the
directives on renewable energy, CHP and emission trading). In addition, one should reflect on an ‘ideal’ fully consistent framework for a fully integrated European electricity (and gas) market, so as to establish appropriate boundary conditions for the overall EU generation system (centralized versus decentralized, generation mix, geographical location of generation capacity, dispatchable or not).

The following aspects need therefore be studied:

1. Analysis of the current legislation & regulation of the liberalized market, the directives on renewables and CHP, and on emission trading;

2. Specification of ‘boundary conditions’ and ‘guidelines’ for proper functioning of future energy markets.

Although it is not certain that the future European electricity provision context (of 2030 – 2050) will be based on an integrated liberalized market, it is a basic hypothesis of the present study that the current trends of liberalization and EU-wide integration will continue to develop, culminating in an optimal liberalized sustainable energy market. On the one hand, the guidelines for a liberalized market will influence the electricity generation setting: incentives for new capacity building, consequences of network congestion and newly constructed cross-border transmission lines, rules of the game concerning availability of, and easy access to, gas transport lines, needed reserve capacity, degree of penetration of correlated fluctuating generation capacity, etc. Conversely, the nature of generation capacity, e.g., centralized versus decentralized, base load versus peak load, easily dispatchable, etc, has consequences for the implementation of the market. In addition, the consequences of the directives for renewable electricity, combined heat & power (CHP), and emission trading, must be evaluated with respect to the liberalized market, on the one hand, and the composition and location of the different components of EU electricity generation system, on the other hand.

A fundamental challenge of a future integrated electricity (and gas) market is the guarantee of a secure supply at affordable cost, through sufficient generation capacity and cross-border transmission capability, but in an environmentally friendly way. As said above, the future energy markets are supposed to be liberalized and fully integrated (subject to an appropriate regulatory framework).

In practice, it is first analyzed what the current state of affairs on the electricity market is, starting from the Commissions DG TREN’s Strategy Working Paper “Medium term vision for the internal electricity markets”[12]. Clearly, reference will be made to the recent ‘Directive on the electricity market [2003/54/EC]’, the “Regulation on cross-border exchange [1228/2004]”, the “Proposal on a directive for infrastructure investments [COM (2003) 740]”, as well as to the “European Regulator’s Group” [13] and the “Florence Forum” [14]. In addition, the “Directives for supply of renewable electricity” [15], and “CHP” [16] on the one hand, and the “Directive on emission trading” [17], on the other hand, will be scrutinized as to their influence on the proper functioning of the integrated market and the security of supply.

In the second part this regulatory topic, the project partners will reflect upon an ‘ideal’ type of regulatory framework and will propose guidelines and boundary conditions to be used later in scenario runs.

2.6 Most Optimal Solution for Electricity Provision

In the next steps, the information and the wisdom obtained from the earlier phases needs to be ‘collected’ and brought into a form that is usable for scenario simulation. This refers, on the one hand, to the energetic, environmental and economic data characteristic for the technologies considered in Section 2.4. On the other hand, the demand for energy services and the projections for electricity demand are likewise collected. Also, at this stage the country-related aspects, such
as the nature and the characteristics of the electricity generation systems, as well as the geographic
differences in demand for energy services and electricity, are introduced here. Furthermore, the
whole synthesis exercise takes into account appropriate boundary conditions of a consistent
regulatory framework for sustainable energy markets.

A first exercise is to establish a summary of the ‘static’ private cost of generation technologies. The “static”
cost is obtained through discounting of investment cost, maintenance and operational
costs at rated conditions of the technology. In order to have meaningful projections towards the
future, each of these costs is to be ‘reconsidered’ in the light of the market-diffusion possibilities
and realities. Next, the so-called hidden costs are to be looked at. This refers to back-up costs,
risk-premium costs in case of ‘unilaterally’ relying on a single primary source, etc. In a further
stage, the environmental aspects are grouped together, but also taking into account the (hidden)
lifecycle emissions, as well as the country-dependent system-related effects. From all of the above
costs and the effects, the overall external costs can be evaluated, which in turn leads to the total
’sstatic’ social cost.

This ‘static’ cost computation is to be contrasted with the overall social cost found as a result from
scenario-simulation codes, whereby the codes themselves determine the evolution of the demand
for energy, the investments in end-use or supply-side technologies, and the shift between the
different energy carriers (all taken into account the external costs, price elasticity etc.). Also, the
‘true’ cost obtained by simulation codes should take into account partial-load conditions and
interaction within the whole system.

In order to do a good job, it is important to make an in-depth comparative analysis of the different
currently used scenario-simulation codes; so as to identify their major differences and to delineate
their domains of application and complementarities. Furthermore, the different existing scenarios
on electricity generation should be scrutinized.

Indeed, a variety of scenario-simulation codes exist and are being used. Each of these codes has its
merits, but it has been insufficiently reported how the boundary conditions and hypotheses behind
these codes and their inputs influence the results. It is therefore necessary to make an in-depth
comparison of these models and codes, whereby their strengths and weaknesses are clearly
identified. Equally important is the identification of the part of “application space” where these
codes are applicable and to find out how they can be complementary. If some cover similar
domains of application, then means to validate them should be stipulated.

The most suitable models and codes should then be used to perform a limited number of some
typical (preferentially contrasting) scenarios. From the different results due to different codes (for
the same scenarios), an effort will be undertaken to clearly understand the reasons why they are
different, leading to particular conclusions on the models and their input. In addition, from the
different scenarios, it should be possible to understand the dynamics of the electricity provision
system (interacting with the overall energy ‘context’ with its different constraints, including
regulatory elements related to fully integrated markets and GHG-reduction strategies). These
scenarios must in principle permit to find the ‘most optimal’ type of electricity provision (from a
total minimal social-cost viewpoint).

The above is structured as follows:

1. Determination of the overall static social cost for electricity
   i) Summarize private cost for generation technologies and project to the future, taking
      into account technology diffusion;
   ii) Considerations on ‘shadow costs’ such as back-up costs, risk premium etc;
   iii) Identification of the differences in CO2 emissions due to electricity generation,
       depending on the different generation systems in the EU-25 countries;
   iv) Determination of global external costs.
2. Comparison and evaluation of simulation models & codes and existing scenarios for electricity generation

3. Performing and interpreting four (contrasting) scenarios with one or two of the most appropriate models (with ‘improved’ input data)

i) Scenario 1: according to present policy in different EU-25 countries (maybe revisiting of existing scenarios);
ii) Scenario 2: e.g., total nuclear phase out in EU-25 with stringent post-Kyoto limits;
iii) Scenario 3: e.g., overall nuclear renaissance in EU-25 with stringent post Kyoto limits;
iv) Scenario 4: based on the interpretation and conclusion of Scenarios 1, 2 & 3.

2.7 Compatibility Check and Validation

The ‘most optimal solution’ obtained in Section 2.6 should not be a mere ‘academic’ result, but it must be scrutinized with respect to the real-life expectations of different players on the energy scene. In addition, the solution must be compatible with the dynamics of the liberalized markets and must offer a sufficient degree of security of supply. Lessons can also be learned from comparison with other enveloping international studies.

To guarantee that the results of the ‘most optimal solution’ are well defendable, it is necessary to do several ‘quality control checks’. These checks are performed continually throughout the project through cross reviewing, but mainly by critical reviews and feedback from the ‘Special-Focus Industrial Advisor’, Eurelectric. In addition, at particular instances during the project, structured interactions with other stakeholders in the Consultative Committee, are organized.

To guarantee that the results of the ‘most optimal solution’ are well defendable, it is necessary to do several ‘quality control checks’. These checks are performed continually throughout the project through cross reviewing, but mainly by critical reviews and feedback from the ‘Special-Focus Industrial Advisor’, Eurelectric. In addition, at particular instances during the project, structured interactions with other stakeholders in the Consultative Committee, are organized.

Mutual interaction with members of the Consultative Committee (CC) will be organized. First, the Consultative Committee will be invited to the mid-term assessment meeting and the final meeting. In addition, three times during the two-years lasting project, i.e., after 8, 14 and 20 months, respectively, a dedicated workshop with the CC is planned to help ‘qualify’ the results obtained under the previously discussed topics in the Sections above. During these workshops, detailed discussions on the project’s results can take place. The CC will be invited to write a statement on the results of the project.

The CC is composed of about 10 persons, coming from,
- EURELECTRIC, ‘Special-Focus Industrial Advisor’, representing the electric industry of Europe;
- two energy-conversion manufacturers (one non-nuclear: Alstom, one nuclear: BNFL-Westinghouse);
- an architect engineer (Tractebel Engineering);
- the umbrella organizations VGB, Erec, Eurogas, Euracoal and Foratom;
- the organizations UCTE and ETSO
- a representative of the CEU DG-Energy will be invited.

In addition to the above check, an External Peer Review Exercise, at the same time of the 2-nd Consultative Committee workshop (i.e., a mid term assessment), will be organized. This independent quality-control check will focus on the objectivity, reasonableness (‘correctness’) of the work. This Committee should work with independent experts and should contain about 4 people (not counting the EU-Commission responsible officer).

Two additional particular consistency checks need to be performed, the compatibility with, and the influence of, liberalized markets and the check with regard to security of supply. Based on the outcome of this “reality check”, possible feedback to the scenarios is foreseen.

It must be verified that all results obtained are in accordance with the reality of liberalized markets, as set out in Section 2.5. In short, issues such as cross-border transmission capacity and
congestion must be checked. In addition to trade, there is the need for back-up power if large amounts of correlated fluctuation power generation is present. Furthermore, the issues of investment in transmission capacity, sufficient base-load and peak-power capacity, dispatchability of decentralized generation will have to be considered. In this respect, the difference between (time-) average power, or energy, and instantaneous power is of utmost importance. As such, the consequences of consistent basic regulatory rules for a secure electricity provision in an integrated European market will be illustrated.

Security of supply is another aspect that must be guaranteed by the ‘most optimal solution’. This requires that one confronts the requested generation mix with the availability of primary sources (such as gas) and at what price. In this respect, some aspects of the California electricity crisis in 2000 might be useful to reflect back on. In addition, the results of the above exercise have to be checked against the findings of the EU’s Green Paper on Energy Security “Towards a European strategy for the security of energy supply” [18], and the recent analysis “European Energy and Transport; Trends to 2030” – January 2003 [5]. The major black outs of the summer/fall 2003 in North America, Denmark/Sweden and Italy will carefully be reflected upon.

Finally, in the last element, the global result for Europe and the methodology is to be held against the light of global (enveloping) international studies (such as the European reports mentioned above [1-4], the WEC/IIASA’s study on “Global Energy Perspectives” [19], the EU’s “World Energy Technology and Climate policy Outlook; WETO” report [20], IEA’s “World Energy Outlook” [21], the UNDP/UNDESA/WEC report on “World Energy Assessment” [22], amongst others. In addition, it would be interesting to compare the European outcome with other OECD countries such as the USA and Japan (for the USA, e.g., National Energy Policy Report, May 2001 “Reliable, affordable and environmental sound energy for America’s future” [23], and the EPRI’s Electricity Technology Roadmap –1999 and 2003 Summary and Synthesis [24]).

In summary then, the compatibility check and validation is organized as follows:

1. Timely consultations with the Consultative Committee
2. Mid-term assessment peer review of the results
3. Compatibility with liberalization of the electricity and gas markets
4. Cross check concerning security of supply
5. Compatibility and validation with other international studies

3 Conclusion

The project EU-SUSTEL aims at providing a fully consistent framework for a secure electricity provision, that is at the same time environmentally friendly and affordable. From the methodology as set out in the paper, it must be possible to obtain the ‘most optimal solution’ (from an economic-effectiveness point of view —including environmental burdens) for the electricity provision in Europe. Results of the study are expected early 2007.

4 Acknowledgements

This work is supported by the EU Commission DG Research (FP6), under contract number Contract 006602 (SSP6) – EUSUSTEL. The authors like to thank the EU Responsible Officer, Domenico Rossetti, for his constructive help in the project implementation, and the project partners: University of Leuven (KULeuven) Energy Institute, BE (R. Belmans / S. Proost); Inst. of Energy Economics and Rational Use of Energy, Universitaet Stuttgart, DE (A. Voss); Advanced
References

1. www.iea.org


7. http://www2.dti.gov.uk/energy/whitepaper/


Session 2 – Emerging technologies

Chairman: Hans Larsen, Risø National Laboratory, Denmark
Energy End-Use Technologies for the 21st Century

Stephen Gehl,1 Harald Haegermark,2 Hans Larsen,3 Masao Morishita,4 Nebojsa Nakicenovic,5 Robert Schock,6 and Tuomo Suntola7

1. Electric Power Research Institute, Palo Alto, California, U.S.A.
2. CHH Consulting, Stockholm, Sweden
3. RISØ National Laboratory, Denmark
4. Tokyo Electric Power Co., Tokyo, Japan
5. International Institute of Applied Systems Analysis, Laxenburg, Austria
6. Center for Global Security Research, Livermore, California, U.S.A.
7. Suntola Consulting Ltd., Espoo, Finland

Abstract

The World Energy Council’s recent study examined the potential of energy end-use technologies and of research, development, and demonstration (RD&D) into these technologies on a global scale. Surprises are likely, but nevertheless, current research and development offer a picture of what might happen in the future as new technologies face the competition of the marketplace. Given the breadth of energy end-use technologies and the differences between regions and economic conditions, the study focused on technologies that appear most important from today’s vantage point. Globally, robust research and development followed by demonstrations of new end-use technologies can potentially save at least 110 EJ/year by 2020 and over 300 EJ/year by 2050. If achieved, this translates to worldwide energy savings of as much as 25% by 2020 and over 40% by 2050, over what may be required without these technologies. It is almost certain that no single technology, or even a small set of technologies, will dominate in meeting the needs of the globe in any foreseeable timeframe.

Absent a significant joint government–industry effort on end-use technology RD&D, the technologies needed will not be ready for the marketplace in the timeframes required with even the most pessimistic scenarios. Based on previous detailed analyses for the United States, an international expenditure of $4 billion per year seems more than justified. The success of new energy end-use technologies depends on new RD&D investments and policy decisions made today. Governments, in close cooperation with industry, must carefully consider RD&D incentives that can help get technologies from the laboratory or test-bed to market.

Any short-term impact areas are likely to benefit from focused RD&D. These include electricity transmission and distribution, distributed electricity production, transportation, the production of paper and pulp, iron and steel, aluminum, cement and chemicals, and
information and communication technologies. For long-term impact, significant areas include fuel cells, hydrogen fuel, and integrated multi-task energy systems.

1 Introduction

The World Energy Council’s 2004 study, *Energy End-Use Technologies for the 21st Century*,¹ was aimed at understanding the role that new energy technologies may play in accelerating energy improvements throughout the world—to meet increasingly stringent environmental standards and to broaden the commercial availability of energy and energy services. This study examined the potential of energy end-use technologies and of research, development, and demonstration (RD&D) into these technologies on a global scale. The goals of the study were threefold: to identify important technologies for the next 20–50 years that can increase the benefits of energy; to help define the roles that industry and governments might play in their development; and to determine the investment required to bring these technologies to the stage where the marketplace can decide whether they are useful. This study is believed to be the first attempt to examine the future of energy end-use technologies on a global scale, both geographically and across the energy spectrum. Source and conversion technologies were reported in 2001.² While preliminary, these reports should nevertheless encourage industry and governments to undertake more detailed investigations. While surprises are likely, current research developments offer a picture of what may happen in the future as new technologies face the competition of the marketplace.

Energy carriers transmit energy from the source to the end-use technology. Electricity is produced by the conversion of a source, the local choice made based on economic, reliability, convenience, and environmental factors. Gasoline carries energy from petroleum, and sometimes coal. Natural gas is a source that is also an effective carrier and is often used directly with an end-use technology (i.e., conversion to building heat, grid electricity, or transportation power). Coal is more often converted to grid electricity. Solar radiation may be converted directly into low-grade heat. Hydrogen carries energy from fossil sources (oil, coal, or gas), from renewable sources (biomass) or by conversion from any source of electricity. Each conversion step involves cost (energy losses and capital costs for equipment) and therefore affects economics. Figure 1 is a simplified depiction of the dynamic interplay between energy sources, carriers, and end-use technologies.

Beyond technology, commercialization in the marketplace usually depends on government policies that—at a minimum—do not hinder their introduction, and—at a maximum—may encourage a more rapid and successful introduction.

---


One of the most important issues for end-use technologies is their impact on developing countries. Despite advances in science and technology, the absolute economic gap between developing and developed countries is increasing.\(^3\) Clean, abundant water is crucial to the health and well-being of the population and to a vibrant economy. Energy is a prerequisite. Finally, information and communication technologies (I&CTs) take on critical importance in all areas of human life, including energy technologies, but none more important than end-use technologies. I&CTs are a necessary first step in giving people and institutions in developing countries the knowledge to identify and provide energy services.\(^4\)

### 2 Future Scenarios

The future cannot be predicted and technology breakthroughs as well as surprises are always a reality, yet it is possible using the state of development of the technologies we envision today to look at the historical development of energy technologies and times for technology learning—along with economic considerations, environmental, investment, and other constraints—to gain insights into potential development paths for energy technologies.

---

3. The gap appears to be decreasing on a per capita basis, as the two largest population countries, China and India, develop their industrial base. See, for example, *The Economist*, 13–19 March 2004.

Earlier studies were updated for this assessment of end-use technologies and scenarios were chosen covering a range of economic and environmental conditions and include the 6 scenarios developed in *Global Energy Perspectives* (GEP)\(^5\) and 28 developed independently for the *Special Report on Emissions Scenarios*.\(^6\)

This study focused on two timeframes: 2020 and 2050. Three extreme scenarios were considered to understand what the high and low demand might be. Two of the scenarios can be characterized as futures of high economic and energy growth as a result of successful globalization efforts (A in GEP, and specifically both A1 and A3, high fossil or low fossil), and the other as ecologically driven with reduced energy consumption due to increased efficiency and energy conservation (C in GEP), specifically C2, which contains nuclear power and renewables. The A and C scenarios represent the effective range of possible futures.

The three scenarios are generally described as follows:

- **A1**—High-growth scenario that goes beyond conventional wisdom on the availability of oil and gas. No remarkable developments favoring either coal or nuclear. As a result, technological change focuses on tapping the vast potential of conventional and unconventional oil and gas. Oil and gas could be replaced by coal, the gross amounts of energy used staying the same.

- **A3**—High-growth scenario with transition to post-fossil energy. Large-scale use of renewables with intense biomass utilization and a new generation of nuclear technology. By 2100, nearly equal reliance on nuclear, natural gas, biomass, and wind and solar renewables.

- **C2**—Reduced energy consumption and unprecedented progressive international cooperation focused explicitly on environmental protection and international equality using nuclear and renewable energy. Technically challenging with a new generation of inherently safe, small-scale nuclear reactors and abundant renewable energy.

Despite enormous differences in energy source assumptions across the scenarios, they share the same assumptions about the availability of fossil- and nuclear-energy resources and renewable-energy potentials. But their deployments differ, depending on assumptions about rates of technological learning, economic development, and other forces. These differences tend to be amplified after 2020. Because of the long lifetimes of infrastructure, power plants, refineries, and other energy investments, there will not be a sufficiently large turnover of such facilities to reveal large differences in the scenarios before 2020.


3 General Implications for the Future

In general, the quality of energy end-use services improves across all scenarios to a degree independent of alternative primary energy transitions. Electricity and natural gas are expected to continue to increase within this overall transition toward a more important role for grids, and new energy carriers such as hydrogen become ever more prevalent only toward the end of the century. The role of liquids stays roughly the same with a gradual transition toward synfuels, such as methanol, diesel or gasoline from coal, and ethanol from biomass. The most striking of all transitions is the radical decline in the use of solids. This leads to an important reduction of adverse environmental and health impacts. Solids are increasingly converted to electricity, energy gases, and liquids.

In summary, key technologies are those that improve energy efficiency, renewable energy, and the next generation of fossil and nuclear energy. RD&D carried out now is crucial to the realization of any scenario. Accumulation of experience (technology learning) is vital and this takes time. In the early stages of RD&D programs, cooperation (as between industry and government) is important to ensure interruption-free technological progress with minimal redundancies. Gases—first natural gas and then hydrogen—gradually replace solid and liquid fuels. Hydrogen, while making significant inroads before 2050, predominates only after. A principal reason is that natural-gas conversion and utilization technologies are already well advanced.

4 End-Use Technologies

4.1 Industry

Currently, industry consumes 30% of the world’s energy. The A and C scenarios indicate an industry sector worldwide using 165 to 285 EJ per year in 2050 compared with approximately 115 EJ today, a 143% to 250% increase. The energy savings due to new technologies, estimated by taking the difference between A and the C (technologically challenging) scenarios can be as much as 120 EJ per year by 2050, with over 80% likely in Asia. The energy-intensive industries paper and pulp, iron and steel, aluminum, cement, and chemicals are emphasized because together they are responsible for the vast majority of global energy consumption by industry. Emphasis is also given to the service industry because of its increasing economic importance, both to developed countries and to countries in transition.

Most energy-intensive industries implement complex processes having long economic lifetimes and requiring large capital investments. Process changes in such industries are rarely done for energy efficiency alone and new energy technologies only come into play either when a major capital change is done for reasons such as market changes or when new plants are constructed. A consequence is that newly industrialized countries often have more modern and energy-efficient plants than traditional production countries. For example, the steel industry in South Korea has far lower energy intensity than the U.S. steel industry. The largest share of work in the service industries consists of office work using computers, copiers, communication equipment, and other appliances. The relationship between development and energy efficiency of computers and office equipment is illustrated in Figure 2.
Some important driving forces and areas for technology development are new and profitable products: process integration including heat recovery and co-generation of electricity; efficient use of raw materials including recycling, energy efficiency, and decreased emissions contributing to sustainable development; and decreasing environmental impact of both production processes and product use. Several new electro-technologies have been identified that show promise for the future. Examples are steelmaking with microwaves and ethylene production. There is also ample scope for improvement in energy efficiency in the short term in these industries. Many other studies of industrial energy efficiency point out that there is considerable scope for improvement even with existing technologies.

4.2 Buildings

Currently, buildings consume slightly more than 30% of the world’s energy. The A and C scenarios indicate that the buildings sector worldwide may be using between 138 EJ and 229 EJ, a 115% and 190% increase over today. Global energy savings can be as much as 20 EJ/year in 2020 and 90 EJ/year in 2050, with Asia, Europe and North America, being the largest users today, having also the largest potential savings from introducing new technologies.

Residential and commercial buildings typically last for many years—30 to 50 years and some much longer, at least in the developed world. Hence, many of today’s buildings will likely still be standing in 2020 and 2050. Parts of buildings may be changed through modifications and retrofitting—improved insulation, new windows and doors—perhaps as often as every 10 or 20 years. However, appliances within the buildings will be replaced at a much higher rate. An important part of buildings of the future are sensors, monitoring systems, and intelligent systems to manage energy use. Thus, the building envelope will adapt automatically to changing needs and conditions (Figure 3).
It is difficult to draw general conclusions about the energy demand of the developing countries and the potential for savings in their residential buildings because of the wide range of climatic, geographic, and socio-economic conditions. Nevertheless, the majority of inhabitants are poor and are likely to remain so, at least in relative terms, for some time in the future in spite of best efforts to alleviate their poverty. This means that low-cost or zero-cost options for saving energy and improving residential energy use and comfort levels are of critical relevance—equal to improving access to affordable, non-polluting energy sources. While it is often imagined that energy conservation is not immediately important for developing countries, there is convincing evidence that the poor spend a significantly higher percentage of income on energy services than the more wealthy due to lower standards of housing, lack of access to modern energy sources, inefficient conversion devices, and other factors.

Compared with other sectors, the building industry in general is fragmented and performs little of its own RD&D, and as such, depends heavily on government innovations and incentives. The industry is active in demonstrations of technology developed by governments (national laboratories and universities). Furthermore, only international (non-governmental) organizations and only a small portion of private industry study future prospects of this sector in the various regions in the world.

### 4.3 Transportation

Transportation is a critical end-use sector of energy. It currently uses about 20% of global primary energy (80 EJ/year) and is expected to grow between 150 and 280% by 2050. Energy savings from new technologies can be as much as 105 EJ/year in 2050. The largest savings by region (20% of total) is estimated to take place in the states of the former Soviet Union, with one-half the total achievable by 2030. Transportation provides people with mobility, and because much of the primary energy comes from petroleum, it is the sector most at risk of being disrupted, either by economic conditions or political situations. There is
no evidence of saturation in the markets for transportation services in developed countries. When coupled with rapid growth in developing countries, it places emphasis on the future of the transportation end-use sector, assuming that future growth can be supported by national economies.

A closer examination of the three scenarios considered in this study yields an insight into the end-use demand for transportation services worldwide and its prospects. The scenarios project an increase in air and road traffic of close to 200% in the next 50 years. However, although much smaller now, rail and water traffic may grow by more than 500% by 2050 reflecting a much larger population and a drive toward mass transit. Nevertheless, a doubling of the air and road passenger traffic over the next 20–30 years, with two-thirds of all traffic using these means, places a great deal of pressure on automobile and air transport technologies. Not to be overlooked is freight traffic that already accounts for 30–40% of energy use in the transportation end-use sector and is projected to grow by a factor of three over the next 50 years.7

Internal combustion engines (ICEs) are being continually improved and they are likely to be the dominant motive force for the next 10 to 15 years, at least. Alternative-fuel vehicles have already penetrated the markets in a small way globally and in major ways in some select markets (Brazil, intra-city buses worldwide). They will likely continue to make inroads for at least the next 50 years, driven by the need to have alternatives to petroleum and aided by advances in ICEs. Hybrid-Electric Vehicles are just beginning to make inroads and will continue to do so, first with mild parallel hybrids and then with more and more powerful electric motors. This technology is also driven by the need to replace scarce petroleum supplies (more crucial in some countries) through both more efficient use and the choice of alternative fuels. Fuel cells, together with hydrogen fuel, while making inroads into markets in the near-term, will have difficulty competing with engines and alternative fuels, often in hybrid vehicles, until enough technological research has been done to enable them to compete. The timeframe for this is likely to be 30–35 years, although with more intensive research this major market penetration could be sooner.

4.4 Crosscutting Technologies

Crosscutting technologies, those that have the potential to broadly and significantly affect the entire end-use of energy, are also important. They may or may not be energy technologies themselves. General crosscutting technologies that have uses more broadly in society are nanotechnology, biotechnology, information technology, and automation and robotics. Perhaps the best example is the fuel cell, an energy technology that may prove useful for both stationary and mobile applications.

When will fuel cells become cost-competitive? The price of fuel cells must drop from the present $10,000 per kilowatt to around $3,000 per kilowatt for remote stationary power, $1,000 per kilowatt for grid-power systems, and $100–300 per kilowatt for automobiles. Utility generation systems now cost up to $2,000–3,000 per kilowatt.

Electricity and natural-gas transmission and distribution (T&D) technologies are the means by which the benefits of energy are made available to customers, the end-users of energy. T&D losses account for 7.4% of electricity consumption in OECD countries and 13.4% in developing countries. Despite the promise of the future of power delivery technologies, the current reality is that delivery systems throughout the developed world cannot satisfy the increasing complexity of the market place or the increasing digital needs of the 21st century. Meeting the requirements of the future will require substantial upgrades in three broad categories:

- load growth and replacement of aging assets;
- reliability of the power delivery system with additional investment needed to make up for reduced expenditures in recent years;
- smart power systems with greater functionality for consumers and the ability to reliably support the digital society.

Advanced energy-storage systems are critical to the long-term deployment of intermittent (renewable) energy supply technologies. These include mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen), purely electric or magnetic (ultracapacitors, superconducting magnetic storage), pumped-water (hydro) storage, and compressed-gas (air) storage. The various demands for energy storage shown in Figure 4 illustrate the complexity of requirements for energy storage for a variety of purposes. General goals for energy storage are high reliability, over 85% efficiency, and per-kilowatt costs less than or equal to those of new power generation ($400–600 per kilowatt).

Figure 4. Power and discharge time requirements for energy-storage systems. Highest priority items are marked as is the startup from a complete system blackout. All boundaries of regions displayed are approximate (from Electric Power Research Institute, 2002).
Advances in nanomaterials are expected to be especially valuable in power system applications, from superstrong metal alloys for rotating machinery to tough composites that resist corrosion attack, less-brittle ceramics for power line insulators, and slick coatings that will reduce biofouling in cooling water intakes. Advanced nanostructural catalysts may allow hydrocarbon reforming at very low temperatures (below 100ºC). Successful development of such catalysts would help substantially in making fuel cells that operate at ambient temperatures. Hybrid photovoltaic (PV) solar cells based on conducting polymers and semiconductor nanorods also hold promise; by combining the excellent electronic properties of inorganic semiconductors with the process flexibility of organic polymers, researchers are homing in on PV devices with good efficiencies that are easier and much less expensive to manufacture than conventional solar cells.

Biotechnology includes a particularly rich sub-discipline known as biomimesis—the imitation of natural material and process designs in the engineering of man-made structures and processes. Biomimetic materials, typically offering superior properties and functionality, hold tremendous potential for improving the capabilities of solar photovoltaic cells, enhancing the photo-decomposition of water, for allowing fuel cells to operate at low temperatures.

Other important crosscutting technologies are electronics and semiconductors, automation for industry, measurement and control technologies (see Figure 2), and modeling and simulations.

5 RD&D Investments Required

The study identified an international global cooperative expenditure on energy end-use technologies of at least $4 billion per year as necessary to develop the technologies discussed here to the point where they are ready for evaluation by the marketplace. This conservative estimate does not include monies for significant demonstration activities. This step is much more expensive, as illustrated by the expense associated with the demonstration of known technologies. Absent these efforts at R&D (and then demonstrations), technologies for energy end-use will not be ready for the marketplace in the timeframes required by even pessimistic scenarios of world economic development.
Wind Energy Research at Sandia National Laboratories

Daniel Laird and Tom Ashwill

Sandia National Laboratories
Albuquerque, New Mexico, USA
dllaird@sandia.gov / tdashwi@sandia.gov

Sandia National Laboratories is a multiprogram research facility operated by Sandia Corporation for the U.S. Department of Energy. Established in 1949, Sandia has conducted wind energy research since the mid 1970’s.

Numerous wind energy research efforts are underway at Sandia. Improved computational fluid dynamics capabilities are simulating full three-dimensional flow for the analysis of innovative airfoils. Structural analysis and design tools have produced some interesting results with respect to traditional blade analyses using the finite element method. An advanced data acquisition system transmits data continuously while sub-scale blades demonstrate new concepts. All of these efforts contribute to make wind energy more competitive with other forms of power generation.

1 Sandia National Laboratories

Sandia National Laboratories (SNL) is a U.S. national security laboratory involved in a variety of research and development programs to help secure a peaceful and free world through technology. SNL employs 8,600 people and manages about $2.3 billion of work a year. The U.S. Department of Energy provides primary funding and Lockheed Martin Corporation provides management. SNL partners with a variety of other government, industry, and academic institutions to accomplish the work requirements. In the Energy and Infrastructure Assurance division, technologies are developed to boost production and lower the cost of renewable energies including solar thermal, geothermal, photovoltaic and wind.

2 Wind Energy Technology at SNL

The wind program at SNL began in the mid 1970’s and was focused on vertical-axis wind turbines (VAWT). This work led to the 34-m VAWT Test Bed from 1985 to 1993. This research prototype allowed the study of variable speed and multi-piece laminar flow airfoils on the performance of VAWT’s. Since 1993, the program has focused on industrial-sized horizontal-axis wind turbines (HAWT's).

Today, the Wind Energy Technology department at SNL conducts applied research in several areas to improve wind turbine performance and reduce cost-of energy. Our work resides primarily in two programmatic areas: Low Wind Speed Technology (LWST) and Supporting Research and Technology (SR&T). In LWST, Sandia supports public-private partnerships for multiple large wind systems to achieve the goal of 3 cents/kWh in class 4 winds by 2012. In SR&T, Sandia is conducting enabling research on blades that directly relates to achieving the LWST goals.
3 Current Research

The wind group has been working in several blade research technology areas for many years including computational fluid dynamics, data acquisition, in-flow measurements, load modeling, materials, manufacturing, fatigue, structural analysis codes and adaptive controls. More recently, research concepts are being applied in the development of subscale blades. These blades will allow for a full exercise of the validation loop that consists of design, fabrication, test and data-model comparisons.

3.1 Computational Fluid Dynamics

Successful completion of the LWST blade program requires the accurate prediction of the three-dimensional performance of wind turbine blades. Most traditional blade design tools tend to be steady-state, two-dimensional tools that work only for airfoils with fully attached flow. We need to analyze unusual geometries, including very thick blades (thickness-to-chord ratios > 40%), blades with flat trailing edges, and blades with active control surfaces. These analyses must predict full three-dimensional, time-accurate performance, with significant separated flow. Computational fluid dynamics (CFD) give us many of these capabilities.

CFD codes are not without problems. They require large investment in grid generation, they are computationally expensive, and CFD results often differ significantly from experimental results. The potential lack of accuracy has always been considered to be a huge problem. However, we do not rely on the codes for absolute numbers, but to predict trends and relative changes between configurations. When used in this manner and in conjunction with experimental results from wind-tunnel testing, CFD codes can be extremely useful.

We have extensively used the MSES, ARC2D and Overflow codes. MSES\textsuperscript{2,3} is a two-dimensional, incompressible code. ARC2D\textsuperscript{4} is NASA-developed 2-dimensional, grid-based, Reynolds-averaged Navier-Stokes (RaNS) code, incorporating several turbulence models and an envelope-type turbulent transition prediction. Overflow\textsuperscript{5} is a three-dimensional, compressible RaNS solver, utilizing structured block or Chimera overset grids and incorporating several turbulence models.

Blunt trailing edge airfoils reduce the adverse pressure gradient on the upper surface by utilizing the wake for off-surface pressure recovery. This mitigates flow separation, provides enhanced aerodynamic performance in the form of increased maximum lift and increased lift-to-drag ratios, and decreases the sensitivity of the maximum lift to roughness on the leading edge (insect accumulation and weathering). Figure 1 illustrates the shape of such an airfoil and compares the predicted pressure distribution on that airfoil with a more conventional, sharp trailing-edge airfoil. Figure 2 presents the predicted lift coefficients for the two airfoils. The fixed transition case corresponds to roughness on the leading edge. The flow around such an airfoil is massively separated and highly three-dimensional under most operating wind turbine conditions. Figure 3 presents Overflow results illustrating the highly turbulent nature of the wake flow at a -1° angle of attack for one of these airfoils.
Figure 1. Comparison of Blunt Trailing Edge Airfoil with a Conventional Airfoil.

Figure 2. Comparison of Blunt Trailing Edge Airfoil with a Conventional Airfoil.

Figure 3. Wake Structure For a Blunt Trailing Edge Airfoil at -1° Angle of Attack
3.2 Data Acquisition

Background

Wind energy researchers have historically been forced to utilize long-term summary data from wind turbines supplemented with representative ten-minute time-series data. This assumes that this information is sufficient to define the wind-generated turbine loads and the turbine response. Premature turbine failures and measurements of loads far in excess of predictions have forced reexamination of this assumption. Significant but infrequent events that drive turbine fatigue lifetimes are often missed with traditional data acquisition techniques. Continuous long-term time-series data are needed to capture and analyze these very infrequent events.

ATLAS System

To address this need, the Accurate Time-Linked Data Acquisition System (ATLAS\textsuperscript{6,7,8}) has been developed to acquire continuous, long-term, time-synchronized data from multiple data acquisition units for a period of weeks or months. The system has been used in several testing campaigns since its initial development in 1999. The current version, ATLAS II, utilizes several data acquisition subsystems (DAS) and an acquisition computer, see Figure 4. A basic configuration consists of one rotor-based DAS unit (RBU), and at least one ground-based DAS unit (GBU). All units are installed close to the sensors to minimize contamination of the data by electrical noise. The acquisition computer, equipped with the ATLAS II data acquisition software, is used to program the individual units, monitor/acquire the data and store the data chronologically. The RBU must meet the toughest operating requirements in terms of size, weight, robustness, and immunity to vibration and rotation. Because many wind turbine rotors are not equipped with slip rings to transmit data, the RBU is also equipped with optional 2.4Ghz frequency-hopping, spread-spectrum radio modems.

All units can collect data from analog, digital, or strain gauge channels and are enclosed in an environmentally protected aluminum NEMA box with lightning protection on all channels. AC power has been removed from all of the DAS units to reduce electronic noise and to improve high ambient temperature operation. A power pack (in a separate NEMA box) containing lightening protection, noise suppression circuitry and an uninterruptible power supply (UPS) now provides each DAS with DC power. The UPS provides power for approximately 50 minutes if AC power is lost. The ATLAS II software includes web access, e-mail features, and event triggering.

A recent test of the system, on a heavily instrumented commercial-size turbine, utilized three GBU’s and one RBU, see Figure 4. The GBU’s were located in the nacelle, the base of the turbine, and at the met tower. There were 67 channels at 40 Hz acquired simultaneously. The nacelle GBU was configured to acquire 16 analog signals ranging from nacelle acceleration to azimuth position. A GBU at the met tower was used to collect data from 11 analog meteorological signals. Nine strain gauges from the blades and the low speed shaft were acquired with the RBU and the data was transferred via slip rings into the nacelle, where a fiber optic modem transferred the data to the master unit. The master unit merged all data streams from the other units with the 7 controller analog signals and the 3 tower strain gauge channels into a single data stream for acquisition. The software then segmented the data into 10-minute blocks, converted to engineering units, compressed and stored the data to a separate computer. Each 10-minute record was approximately 16 Mb resulting in 2.3 Gb of uncompressed data daily.
During a four month data collection period, over 17,000 records were collected (285 Gb). During the entire test, a 100% availability was attained by the ATLAS system.

3.3 Finite Element Modeling

NuMAD

Due to the complex geometry of modern wind turbine blades, structural modeling using the finite element method (FEM) is usually difficult and extremely time-consuming. Twisted and tapered geometries, internal support structures, and involved material schedules all contribute to the model complexity. In an effort to increase the usability of advanced finite element analysis capabilities and reduce model development time for wind turbine blades, a software tool, NuMAD (Numerical Manufacturing And Design), has been developed.\textsuperscript{9}

NuMAD is a stand-alone, user-friendly, windows based (graphical) pre-processor and post-processor for the ANSYS\textsuperscript{®} commercial finite element engine. It is not a modified version of ANSYS and may be run either independently to create ANSYS\textsuperscript{®} input files for later batch execution or in conjunction with ANSYS as a seamless interface. It is designed to enable users to quickly and easily create a three-dimensional model of a turbine blade and perform static structural, modal, and buckling analyses. An example of the NuMAD interface is shown in Figure 5. Experience with ANSYS is not required but knowledge of FEM is needed to use NuMAD effectively.

Shell element limitation

As part of SNL’s manufacturing research, NuMAD/ANSYS analyses of an experimental bend-twist coupled blade found that the torsional response of FEA (Finite Element Analysis) models appeared to be incorrect. Torsional stiffness from blade models varied in an unacceptable fashion in the spanwise direction. Further investigation demonstrated that the torsional stiffness varied even for blade segments of constant section.
Based on these results, numerous models were generated to test the accuracy of shell elements for the simple case of an aluminum, cantilevered hollow tube. The same physical cylinder was modeled with three different element configurations. The first was an 8-node layered shell with nodes at the mid-thickness (default formulation), the second was an 8-node layered shell with nodes at the exterior surface, and the third was a 20-node structural solid element. The two element configurations using layered shells required nodal locations at two different radii to represent the same physical cylinder. For torsional loading, the loads were scaled to obtain the same twisting moment. The solid element was investigated to examine the feasibility of utilizing solid elements rather than shell elements. For all analyses, the FEA results were compared to the closed form solutions.

Though all element formulations were accurate for bending, the shell elements with offset nodes proved to be inaccurate with respect to torsional stiffness and shear stress due to torsional loading. An example of the erratic behavior is shown in Figure 6. This case involved varying the element aspect ratio while keeping other parameters constant. Shown is the error in the maximum shear stress at the mid-span of the hollow cylinder. Both the structural solid elements and the layered shell elements with nodes at the mid-thickness performed well throughout the range studied.

![Figure 6. Error in shear stress as a function of aspect ratio](image)

Figure 6. Error in shear stress as a function of aspect ratio
For shell elements with nodes offset to the exterior surface, the solutions were highly inaccurate over most of the range studied. The error decreased significantly as the aspect ratio approached the upper bound of 20. For an aspect ratio of 1, the error was 40% and at its highest point (aspect ratio = 0.38) the error reached almost 80%.

It was eventually concluded that the problem is not in the ANSYS implementation of current FEA theory. As a simple verification of this conclusion, the type of errors presented here for the hollow cylinder with a torsional load has been reproduced in other commercially available FEA codes. The problem appears to be a general limitation in FEA theory rather than a particular vendor's implementation of the theory.

The results of this study have rather profound implications for full-blade structural analyses performed to date. To the authors' knowledge, all of these analyses using FEM have used layered shell elements with offset nodes. Thus the behavior presented in Figure 6 will apply to all of these previously generated models.

The standard method of modeling full wind turbine blades with FEA, layered shell elements with offset nodes, is inaccurate with respect to torsional stiffness determination and shear stress due to torsional loading. Alternative element configurations (solid elements) exist to solve these problems and should be seriously considered for the designs of twist-bend coupled wind turbine blades.

3.4 Blade System Design Studies

In 2000, DOE, NREL, and SNL initiated a series of WindPACT (Wind Partnerships for Advanced Component Technologies) scaling studies to determine the issues and constraints associated with components such as the drive train, tower, rotor and blades when scaling turbines from 1 to 10 MW. The WindPACT studies showed that there were only a couple of constraints identified for blades up to 70 m in length. Onshore transportation is limited to blades in the 52-55 m range due to restrictions in weight, length or height\(^\text{11}\) (For the offshore case, transportation constraints may disappear if the blade fabrication facility is close to shore.) A second limitation is gravity itself. At some point, as blades grow in size, the oscillating loads due to gravity become prohibitive. It is hoped that making blades lighter and stronger can postpone that limitation.

As part of the WindPACT project, the Blade System Design Studies (BSDS)\(^\text{12,13}\) looked at developing innovations in manufacturing, materials, and design that would help reduce expected exponential weight-gain with blade growth. The approach used was as follows:

- Investigate and determine design and manufacturing issues and constraints for blades in the 30 to 70 meter size.
- Perform the preliminary design of a 50 meter blade that incorporates innovations to help reduce constraints.
- Design, build and test specific sub-structures and sub-scale components to determine the feasibility of innovations.

Innovations in Design

Several innovations were proposed and evaluated in BSDS\(^\text{12,13}\) including the following:

- an integrated blade design process that designs for relatively simple structures before finalizing the aerodynamic design
• use of a spar cap with constant thickness and width
• use of a “slender” profile
• use of high lift airfoils with modified thickness and shape for least complex and costly internal blade structure in the outboard region.

In this case the “slender” profile refers to the reduction of large chords typically used inboard. This has the effect of reducing mass (good), but also reducing edgewise stiffness (not necessarily good). One airfoil family that can provide the necessary aerodynamic and structural requirements is the flatbacks. Flatback airfoils (Figure 7) provide enhanced flapwise stiffness and lower weight, but have reduced edgewise stiffness. The trailing edge, however, can be strengthened with increased thickness or the use of carbon to maintain stiffness requirements.

![Figure 7. Use of Flatback Airfoils for Enhanced Structural Efficiency.](image)

Flatbacks tend to have high lift, but also high drag. It is predicted that 3D spanwise flow will reduce the higher drag.

Currently, the design and construction of 9-m prototype blades that incorporate the integrated design process and thicker airfoils are underway. 2D wind tunnel tests will be performed at UC-Davis on flatback airfoils to validate performance. The 9-m prototypes will also be flown and modeled to better understand 3D effects.

### 3.5 Carbon-Hybrid Blade Developments

This research effort is in the final stages. Its objective is the production of two 100-kW-sized carbon-hybrid blade prototypes to study potential weight reductions, investigate ways to incorporate both e-glass and carbon in an efficient structural manner, and demonstrate the advantages of incorporating bend-twist coupling.

Both 9-m prototype blades, termed the CX-100 and TX-100, have been designed and fabricated. The CX-100 has a carbon spar cap and a standard e-glass skin lay-up; the TX-100 has an e-glass spar cap and outboard skins that incorporate off-axis carbon material in a triax material form. Figure 8 shows one shell of the CX-100 blade and its carbon spar cap. Figure 9 shows the

![Figure 8. Infused Shell of CX-100.](image)
carbon-biased skins in the TX-100. Laboratory and field testing have started at both Sandia and NREL facilities and include the following:

- Detailed Blade Mass Properties & CG Measurements
- Full Blade Modal
- Full Blade Static
- Full Blade Fatigue
- NDT
- Twist Measurements
- Field - Blade Loads
- Field - Power Performance

The results of these tests will be compared to NuMAD and full system dynamic models in the validation phase.

![Figure 9. Biased Skins Constructed with Carbon Unidirectional/Biaxial Fiberglass.](image)

### 3.6 Adaptive Blades

An important part of our research is the area of adaptive blades. Adaptive blade concepts can be implemented both passively and actively. In either case, the goal is to affect blade response in ways that alleviate fatigue loads and enhance performance. Passively, blades can be designed in a couple of different ways. One is to sweep the blade along the span to create a moment that induces twist\(^{15}\). A second method is to align the primary load-carrying spanwise fibers in an off-axis manner by about 20 degrees, so as the blade bends, it twists more than normal allowing loads to be relieved. Necessary goals are to maintain flapwise strength and maximum tip deflection. Studies have shown that this “bend-twist” coupling is maximized with the use of very stiff fibers, such as carbon\(^{16,17}\). Active devices can also affect blade response in a positive manner. One concept is to incorporate micro-tabs in the trailing edge of the blade that are activated with low voltage several times in a rotation to reduce loads or enhance performance (Figure 10).
Figure 10. Microtabs on Trailing Edge of Blade for Active Control.


10 ANSYS, Inc., 201 Johnson Road, Houston, PA 15342-1300, (412) 746-3304.


INTEGRATED BIOMASS UTILISATION SYSTEM

Charles Nielsen, Jan Larsen, Frank Iversen and Christian Morgen*
Elsam A/S
Overgade 45
7000 Fredericia
Denmark

Børge Holm Christensen
Sicco K/S
Odinshøjvej 116
3140 Aalsgaarde
Denmark

ABSTRACT
Modern waste- and biomass-fired power plants have low electrical efficiency compared to power plants using fossil fuels. The low electrical efficiency is mainly due to the increased corrosion risk caused by alkali chlorides.

Hydrothermal pre-treatment of the primary ligno-cellulosic biomass can reduce this problem.

The leachate from the hydrothermal extraction process has a high content of alkali chlorides and organic compounds, which can be used for ethanol production using a thermophilic bacillus strain. The remaining fibre fraction can be hydrolysed enzymatically and fermented by yeast to ethanol. The ethanol will be suitable for utilisation in the transportation sector in a cost effective and environmentally sound way. The lignin containing presscake can be dried and co-fired with coal in power plants with advanced steam data without corrosion risks.

Elsam is the project coordinator in a large EU project (contract no. ENK6-CT-2002-00650) with the aim of demonstrating this new technology in a bench-scale plant and a pilot plant with a capacity of 1 t/h. The project also comprises a detailed design and feasibility study of a full-scale plant with a total capacity of 450,000 t/y of biomass. The total project budget is approx 13.6 million Euro of which the European Commission funds 6.5 million Euro. The project partners are: the British tmo Biotec, and the four Danish companies Sicco, RVAU, Risø, and Elsam.

The production of liquid fuels - methanol, and as mentioned here - ethanol, is the basis of Elsam's VEnzin vision from 2004). With the VEnzin vision, Elsam's line of products, viz. electricity and district heating, now also includes liquid fuels based on renewables.

In the past two and a half years, Elsam has been the project coordinator of a large EU-project with the aim of demonstrating a new technology for producing fuel ethanol from agricultural residues and household waste. In the course of the project, a pre-treatment reactor with a capacity of 100 kg/h of straw has been designed, built and operated for some 250 hours, and a pilot plant with the capacity of 1 t/h has been designed and built. Valuable design and operational experience from the 100

* Corresponding author: Phone +45 79 23 33 56. E-mail chm@elsam-eng.com
kg/h facility have been incorporated in the design of the pilot plant. In 2002, when the project was initiated, the primary task was to extract alkali metals and C5 sugars (hemicellulose) from straw. The reduced alkali content in the straw improves the combustion properties, making co-combustion more feasible, and the C5 sugars were intended for fermentation with special micro organisms producing ethanol. A number of technological advances have changed the overall process, incorporating ethanol production from the cellulose fraction as well. With these achievements, ethanol yields of approximately 200 kg per ton of straw can be achieved.

**100 kg/h pilot plant**

In 2003, the first pilot plant with 100 kg/h capacity was constructed and brought into operation.

More than 250 hours of operation with the small pilot plant have given Elsam a lot of valuable operation and design experience, and through varying the operational parameters in cooperation with the scientists from Risø and RVAU, a much better picture of the processes has been achieved. A large number of samples of both the solid fraction and the liquid fraction has been analysed by the researchers for sugar yield, fermentability and potential ethanol yield.

On the mechanical side, Elsam has gained valuable experience with the design of the equipment, and this knowledge has been put into the design of the 1000 kg/h plant. Some of the most important findings are:

- The design of the valves in the particle pumps is critical for the operation of the plant
- The (standard) valves installed in the 100 kg/h unit can be kept in operation in shorter periods at a time (app. 1 day), but will not be suitable for continuous operation.
- Different types of valves are needed for the different positions in the process.
- Several new valves have been designed for the 1000 kg/h plant.
- The first reactor was constructed for pressure up to 40 bar, but a process optimum is achieved at a lower pressure.
- The original system for internal recirculation of water/hydrolysate has been modified for the 1000 kg/h reactor.
- With a good recirculation in the system, trials have shown that it is possible to wash out more than 60 % of the hemicellulose in the straw.
- A very good pretreatment process has been achieved with the potential of high yields of ethanol.

**Trials with household waste**

Lightly sorted household waste has been tested in the pilot plant under cold conditions, in order to investigate the mechanical function of the equipment with household waste. The preliminary test showed that the chosen fractions could be transported through the pressurised reactor. No samples were taken out for analysis.

**The first Ethanol**

Preliminary trials with enzymatic hydrolysis and fermentation (including SSF) have already produced the first amounts of ethanol, both at Risø and at Fynsværket.

**1000 kg/h pretreatment plant**

In the autumn of 2004 the first equipment was delivered to the site for the 1000 kg/h pilot plant, and in April 2005, the last component was installed. The 1000 kg/h pilot plant includes the following components:

- Weighing table for registration of the straw input.
- Feeding table with a capacity of 6 bales.
- De-baler
- Stone trap
- Straw cutter
- 3-stage reactor comprising a soaking reactor (will be operated at 80 °C), a new reactor designed for operation at 25 bar/200 °C and the reactor from the 100 kg/h pilot plant, which has been modified in order to increase the capacity to 1000 kg/h.

In May and June 2005, the installation will be completed with electrical installations, piping, steam supply etc., and the plant will be put into operation. The first experimental data is expected in August/September 2005.

**Fermentation unit**

In order to optimise and develop the fermentation process in an industrial scale, a fermentation facility is installed in connection with the pre-treatment facility. The facility includes fermentors of various sizes (5 l, 50 l, 100 l). The combination of fermentors can be used for batch-, fed batch- and cascade fermentation and C6 fermentation followed by C5 fermentation. The facility also includes mobile feeding tanks, control system, and
a 500 l reactor for hydrolysis. The 500 l reactor will be specially designed for liquefaction and enzymatic hydrolysis of the fibre fraction and can also be used for fermentation. Finally, equipment for continuous ethanol recovery will be added. The primary objective of the hydrolysis and fermentation facility is to demonstrate the complete process from straw to ethanol in an industrial scale. For example, the hydrolysis process cannot be fully demonstrated for straw in laboratory scale due to the physical properties of straw. In this facility, it will be possible to investigate hydrolysis of straw (and other pretreated biomass) in a realistic scale. It will also be possible to assess the suitability of all combinations of pretreated biomass, extracted liquid and different types of micro organisms (yeast, thermophile organisms, fungi) for the IBUS process. The size of the fermentation units allows for production of ample amounts of biofuel (residual cellulose and lignin) for large-scale (co)-firing trials.

**Feasibility study**

From the beginning of the project, a detailed feasibility study with a complete model of mass and energy flows has been elaborated. In the course of the project, the feasibility study has provided the design team with valuable information about optimisation of the process and equipment in order to improve the overall feasibility of the concept.

Based on the experimental data, the mass balances have shown, that 200 kg of ethanol can be produced from 1000 kg straw, under the condition that micro organisms, which can produce ethanol from C5 sugar are available.

Detailed energy balances of the process have demonstrated that approximately 55% of the total energy content in the straw remains in the fibre fraction and will be converted to energy (heat and electricity) in the power plant. This in turn will provide enough energy for the complete pretreatment, hydrolysis, fermentation, distillation and drying of ethanol – in fact, a surplus of electricity produced from co-firing the fibre fraction in the power plant can be exported to the grid. Of the total energy content in the straw, 34 % will be converted to ethanol, and 17 % will be sold as electricity from the power plant.

**Integrated Biomass Utilisation**

An essential part of the system is the integration with other facilities:

- Ethanol production from conventional sources (grain, corn etc).
- Power plant supplying low value steam for the IBUS process and converting the lignin fraction to useful energy (heat and electricity).

Plans for an ethanol production facility based on grain and situated at one of Elsam’s power plants are being made, and detailed feasibility studies have been carried out demonstrating a considerable economic benefit in integrating ethanol production with the power plant. The plant will convert 320.000 t/y of grain to 100.000 t/y of ethanol.

Included in the planning of the grain to ethanol plant are all necessary preparations for adding a straw based production facility to the grain based facility. The plant will convert 150.000 t/y of straw to 30.000 t/y of ethanol.

The overall aim is to demonstrate the IBUS system in full scale.

**Information and Communication Technology**

In order to promote implementation of the technology, an Information and Communication Technology (ICT) system is being developed. The ICT system consists of three parts:

- A public website with general information about the project. The website has been established and is updated on a regular basis. The website is located at [http://www.ibusystem.info](http://www.ibusystem.info).
- A website for potential end-users of the technology. It will be possible for potential users to give input data concerning local conditions (prices for biomass, steam, power, site conditions etc.) and receive output from the system concerning the feasibility of establishing an ethanol plant under the given conditions. Modified versions of the models from the feasibility study will form the basis of the ICT system, and a user interface designed by Elsam will be used for exchanging data with potential end-users via the website.
A project web with exclusive access for the project participants has been established, and more than 200 documents have been uploaded to the website.

In addition to the ICT system, the results from the project have been published in a number of scientific papers from Risø, RVAU, Sicco and Elsam. Furthermore, a significant number of students from various educational institutions have made projects in connection with the pilot plant.

**Future work**
The following work is planned for the remaining 12 months of the project:

- optimisation of the pretreatment process for straw
- trials with other raw materials (bagasse, corn stover, palm oil residues)
- development of a system for receiving and handling whole-grain bales
- long term continuous operation of the 1000 kg/h plant (30 days)
- optimisation of the hydrolysation and fermentation process
- development of equipment for handling (drying) the lignin fraction, and determination of the combustion properties.

- improving the quality of input to the feasibility study based on trial results
- completion of the ICT system

**From Petrol to RETrol**
The IBUS project is a part of Elsam’s overall vision for the Danish Energy Sector. The vision is named VEnzin and aims to combine the existing supply system for electricity and heat (power plants, wind turbines, waste-to-energy plants) with production of liquid fuels (ethanol and methanol), which can be blended with gasoline, and utilise the existing distribution system and existing vehicle technology. Ethanol and methanol will be produced from renewable sources, ethanol from straw and other biomass, and methanol from hydrogen produced with electrolysis driven by surplus wind turbine power. The new fuel, which is a blend of gasoline, ethanol and methanol is called RETrol, and the share of fuel in the blend, which has been produced from renewable energy can be increased when the economic situation allows it (as the conversion technologies are improved, the gasoline price goes up, or the politicians request it). Learn more about the VEnzin vision at [http://www.elsam.com](http://www.elsam.com).
The European Hydrogen and Fuel Cell Technology Platform and its Strategic Research Agenda

Prof Lars Sjunnesson
Sydkraft AB, Malmö, Sweden
Lars.Sjunnesson@sydkraft.se

Abstract

In Europe a number of companies, institutions, governmental organizations and similar bodies are involved in the development of fuel cell and hydrogen technology characterized by competition rather than collaboration between the different stakeholders. The work in Europe therefore appears fragmented and as a result leaves Europe, with one or two exceptions, a poor third after the USA and Japan. This is gradually to be changed. The European Commission has launched the Technology Platform for Hydrogen and Fuel Cells, which, most likely, will help to realize and commercialize the different technologies.

The Strategic Research Agenda (SRA) is one of the parts of the Technology Platform and shall provide a strategic outline to stimulate investment in research, provide guidance for policy options and deliver a realistic and inspirational research program that will mobilize stakeholders and ensure that European competencies are at the forefront of science & technology worldwide. It shall take into account the imminent FP7 and subsequent programs, the needs for coordinating R&D with demonstration, deployment and financing.

It shall provide a prioritized 10 years research program, a well-founded mid-term strategy until 2030 and a long-term strategic outlook until 2050. The SRA defines priorities for investment in R&D in the context of Europe’s strengths and weaknesses and later industrial exploitation. Thus, in addition to highlighting certain technologies need to be downselected to the most effective ones.

This research agenda indicates those areas that are vital for the introduction and rollout of hydrogen as an energy carrier from now until 2050. It follows that it is not a full summary of all science and technology that could be pursued in relation to hydrogen but a selected and weighed compilation of strategic research issues.
1 The outline of the SRA

The SRA consists of the whole chain where hydrogen and fuel cells are involved, i.e. Hydrogen production, Hydrogen storage and distribution, Stationary applications, Transport applications, Portable Applications and it also include Socio-economic issues.

Hydrogen production is most likely the most critical area for the future use of hydrogen. Hydrogen storage will be more and more strategic when the use of hydrogen increases. Stationary applications for fuel cells have to compete with already existing technologies. Transport applications have to meet the same challenges as stationary applications but in some cases even harder challenges. The portable area might be the area that opens the market. The socio-economic area is expected to be more and more important.

2 Important applications

1 Fuel cells for vehicles are appraised as the major driver for fuel cell development.

2 Stationary fuel cells are supposed to make a major contribution to CO2-savings via CHP-units.

3 Portable fuel cells are supposed to contribute substantially to an early market introduction of fuel cell technology.

4 Combustion technologies broaden the basis of technological options, thus increasing the robustness of a hydrogen strategy. They bear a considerable potential for niche markets and are expected to help facilitate the market entry of hydrogen technologies.

5 Since hydrogen provides a great flexibility in terms of primary energy and energy use and as it compares favorably to electric power in storage density it has a great potential to complement electricity in its function of a flexible energy carrier.

6 Hydrogen production technologies should be focused on a high potential to contributing to the primary policy goals in a reasonable time: climate protection, security of energy supply and strengthening the European economy. Fossil bridging technologies are important for market entry and for certain applications even in the long-term. Reforming technologies for fossil fuels pave the way for future renewable fuels and biogas.
3 Major drivers

7 A major technological driver for fuel cells is material research. Advances in material performance will give improvements in efficiency, cost reduction and are the key to achieving performance and cost targets for most applications currently under development.

8 Modelling is of utmost importance for innovative systems engineering and materials’ development. This includes systems modelling up to the dynamic level and materials’ modelling as well as lifetime prediction and development of accelerated testing. Experimental verification tools are to be developed.

9 Systems engineering as well as BoP and component development is strongly recommended to be pursued already at an early stage of development.

4 Pre-eminent research areas

10 Hydrogen storage is of utmost importance. Existing approaches need to be pursued and novel storage materials and principles are crucial if not critical. Development criteria are storage density and price as well as efficiency of the energy utilization.

11 Polymer fuel cells operated at elevated temperatures are considered a potentially breaking technology. This technology depends on novel proton conducting materials to be developed.

12 Electronics needs to be introduced to fuel cell development to a higher degree. Map-control of stacks or even single cells is likely to bear great chances. Power electronics needs to be improved in terms of energy efficiency and cost. Sensors, as well as tools for diagnostics and control are crucial.

13 High temperature fuel cells are well suited for use in stationary power generation. The critical path of development is the mechanical integrity of these devices. Their use in APU’s is favored for simple systems design with carbon containing fuels.

14 The existing polymer fuel cell development ought to be brought to the market soon and consequently via further intensive development. It is the backbone of the existing line of fuel cells, hydrogen and alternative fuels. SMEs already have early products and rely on near-term returns on investment.
Key to fuel cell commercialisation is the development of mass production technologies for fuel cell stacks and systems.

Safety aspects are crosscutting to all applications and technologies and should be integral part of all R&D efforts. Specific safety research is required in addition.

5 R&D Budget

The largest share of R&D funding should go into transport applications (27%) as this is the driving force for fuel cell development, followed by hydrogen production (22%), stationary applications (20%) and hydrogen storage & distribution (18%). Portable applications should receive 10% funding for their importance for early market development, but limited energy relevance. Socio-economic research providing long-term guidance should receive a 3% budget share reflecting its great importance, but lack of cost-intensive hardware requirements.

Many R&D issues in fuel cells and hydrogen, especially in basic research, are crosscutting between all areas of application and thus represent an important source of synergy. An overall budget allocation of 16% for basic research and crosscutting issues is suggested.

6 Managerial aspects

Consistency and coherence with the Deployment Strategy will be achieved. One Hydrogen and Fuel Cell strategy is the aim.

Market entry strategies are of utmost importance for the success of fuel cells and hydrogen. This includes markets which are not energy relevant in the first place like military equipment.

Funding timelines need to be aligned with the technical and commercial status of the single technologies, which range from early research to commercial maturity.

Public awareness and acceptance needs to be built for hydrogen and fuel cells based on detailed understanding of attitudes. A strong focus is to be put on continued education of the public and of specialists as well as on professional training.
7 Aspects on further work of the SRA

23 It is of importance to further study the aspects of technology, market and financing also in the strategic research agenda. As important is also to include the outcome of success-projects and all kind of business opportunities.

24 It is also of highest importance to include all stakeholders in the work, i.e. Industry, Market, Universities/Institutes, Governments etc.
Session 3 – Hydrogen Economy

Chairman: Mike Johnson, Rutherford Appleton Laboratory, United Kingdom

Tiina Koljonen¹, Esa Pursiheimo¹, Birte Holst Jørgensen, Per Dannemand Andersen², Annele Eerola¹, Torsti Loikkanen¹, E. Anders Erikson³

¹Technical Research Centre of Finland, P.O. Box 1606, FIN-02044 VTT, Finland
²Risø National Laboratory, P.O. Box 49, DK-4000, Roskilde, Denmark

SUMMARY

The paper presents the results from the Nordic Hydrogen Energy Foresight. The objective of the project was to illustrate the prospects of hydrogen energy technologies, applications and markets, and to analyse the implications in the Nordic context up to 2030. During the project, key hydrogen related technologies were prioritized by Nordic and international experts. The technologies considered for hydrogen production were reforming of natural gas, electrolysis with wind power and biomass gasification. The examination of transport applications focused on hydrogen city buses and new private cars. In stationary applications, fuel cell systems were considered the most feasible technology for centralized and decentralized heat and power production as well as for APS/UPS systems. The context for envisioning the introduction of hydrogen in the Nordic energy systems was set by three ambitious but realistic “big visions”. In these visions, the share of hydrogen in the Nordic energy system by 2030 was estimated to be 6-18% in transport sector and 3-9% in stationary applications. The consequences of realizing the visions were analysed using the linear programming method. A model of a potential Nordic hydrogen energy system was first constructed. The market sizes, investment costs and total costs of the assumed Nordic energy systems were then estimated with the help of the model.

1 Introduction

Hydrogen as an energy carrier has been considered to contribute to the challenges of future energy system: security of supplies and climate change. The development of a hydrogen economy, with hydrogen produced from renewable energy sources, is a long term objective of the European research agenda. Its potential for turning renewable energy such as wind and solar power into storable energy commodity makes it attractive
for the future energy system in Europe.

To make the hydrogen economy a reality in the long run, various options and transition paths should be systematically analysed. A comprehensive systems analysis with the widely used “bottom-up” technical-economic model MARKAL is planned by the IEA Hydrogen Coordination Group to take place in 2005. In the integrated EU project HyWays (www.hyways.de), the European hydrogen energy roadmap will be developed and regional hydrogen supply options and energy scenarios are analysed with MARKAL as well.

This paper gives an overview of the Nordic H₂ Energy Foresight with a special emphasis on the systems analysis and assessment of technological alternatives of Nordic hydrogen energy system. The main part of the paper focuses on the model description and scenario calculations including implications of the envisioned future development in terms of costs and market sizes. The inputs of scenario calculations are reported including a short description of the existing Nordic energy system. Finally, the conclusions on the scenario calculations of Nordic hydrogen systems are discussed.

2 Objectives and design of the Nordic H₂ Energy Foresight

The Nordic H₂ Energy Foresight exercise was launched January 2003 by 16 project partners from academia, industry, energy companies and associations from all five Nordic countries. The Nordic Energy Foresight has the following objectives:

➢ To develop socio-technical visions for a future hydrogen economy and explore pathways to commercialisation of hydrogen production, transport, storage and utilisation

➢ To contribute as decision support for companies, research institutes and public authorities in order to prioritise R&D and to develop effective framework policies.

➢ To develop and strengthen scientific and industrial networks.

The project has centered on a sequence of four interactive workshops: Scenario Workshop, Vision Workshop, Roadmap Workshop and Action Workshop. Expert judgments and discussions in these workshops are assisted and challenged by formal quantitative systems analysis and technology assessment.

The Scenario Workshop discussed the external conditions around the hydrogen society. General issues that cannot be affected by a hydrogen technology policy but are likely to affect introduction of H₂ Energy in the Nordic system were considered. The scenario workshop produced three scenario sketches for Nordic H₂ energy introduction (see Eriksson, 2003):

B – Big Business is Back is a globalised economy dominated by US multinationals and US big business-oriented policy approaches. Major physical investments are not particularly helped by the prevailing quarter-to-quarter capitalism. There is very little interest for global environmental issues. Oil prices are moderate. However, H₂ energy is still believed to be a likely component in future energy systems.

E – Energy Entrepreneurs and Smart Policies is a globalised economy dominated by entrepreneurs and venture capitalists, and with policy actors apt at harnessing the power
of innovation for societal purposes. The energy sector is characterised by a tendency towards decentralisation. There is some interest for global environmental issues. Oil prices are moderate.

**P – Primacy of Politics** is a Europe-centric economy characterised by co-operation between governments and big business and with a great interest in large-scale investment in energy and transport systems. There is some interest for global environmental issues. Oil prices are high due to security-of-supply problems and an important driver for energy sector change.

Combining the above three first-period (2005-2015) scenarios with second-period (2015-2030) developments (1. “hydrocarbon security-of-supply problems”, 2. “undisputable CO2 problems”, 3. “a smooth path to the future”), we got 9 scenarios (see Figure 1). Scenarios B3, E1 and P2 were chosen to form the framework for the subsequent work.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B – Big Business Is Back</td>
<td>Red</td>
<td>Green</td>
<td>B3 Big vision 6%</td>
</tr>
<tr>
<td>E – Energy Entrepreneurs and Smart Policies</td>
<td>E1 Big vision 15%</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>P – Primacy of Politics</td>
<td>P2 Big vision 18%</td>
<td>Red</td>
<td></td>
</tr>
</tbody>
</table>

The colour indicates the ease of Nordic H2 introduction:
- green – easy
- yellow – intermediate
- red – difficult

“Big Vision” indicates hydrogen’s share of the total Nordic energy system in 2030, except for consumption in industrial sector.

*Figure 1. The external scenarios produced on the basis of the scenario workshop.*

At the Vision Workshop, the experts discussed hydrogen technology visions in the Nordic context and issues that can be affected by Nordic actors. Preliminary focusing was made on the most important issues – those with the highest feasibility today and the largest future Nordic market potential. Based on the assessment, the most interesting of the 66 hydrogen technology visions were selected (see Figure 2). For hydrogen production, the main energy source was believed to be natural gas over the next 25 years – especially in the B3 scenario. In the other two scenarios, natural gas might play a smaller but still important role. Renewable energy sources available for hydrogen production in the Nordic countries over the next 25 years are wind power, biomass, geothermal and hydro power. Most of the Nordic countries’ hydro resources are exploited by now, and only remote Iceland and Greenland have non exploited feasible resources. Only Iceland has geothermal resources. Nuclear energy is expected to play an important role in Finland, which could be used for hydrogen production as well. In the Vision Workshop, the energy sources for hydrogen production by 2030 in the three scenarios were settled by 2030 to:

Scenario B3: Natural gas: 70%; Renewable (and nuclear): 30%
Scenarios E1 & P2: Natural gas: 50%; Renewable (and nuclear): 50%

The participating experts were also asked to assess an ambitious but realistic “big vision” for hydrogen by 2030. Hence, hydrogen’s share of the total Nordic energy system by 2030 was assessed as follows:
Scenario B3: 6%-7%  6%
Scenario E1: 14%-16%  15%
Scenario P2: 16%-19%  18%

Figure 2. Ranking of hydrogen technology visions in average over scenarios – based on the vision workshop.

The Roadmap Workshop outlined the sequence of implementation and mutual interdependence of the hydrogen technology visions from today until 2030. The experts discussed the business opportunities for Nordic equipment industry and energy market opportunities for the energy companies in the Nordic countries. This was carried out for each of the three areas (see Dannemand Andersen 2004):

1. Production and production related transmission/distribution of hydrogen;
2. Hydrogen used in the transport sector (including related distribution and retail); and
3. Stationary use of hydrogen (including related distribution and retail)

The Action Workshop discussed the actions needed to overcome barriers and to realize the Nordic hydrogen energy visions and roadmaps. Focus was on the above listed three development areas. In addition, generic cross-cutting issues and conditions as well as possibilities utilizing new business opportunities were discussed (see Eerola, 2004).

The Systems Analysis was carried out to analyse technological and economical feasibility of different hydrogen technologies in different scenarios. The method for scenario calculations and the main results are discussed in the following sections.

A web-site – www.h2foresight.info – informs on ongoing hydrogen related activities, both in the Nordic countries and elsewhere and publishes results generated during and after the foresight process. The entire Foresight process has been described in more detail in earlier project reports and conference papers (Dannemand Andersen et al, 2005; Eerola et al, 2004).

Finally, an evaluation of the foresight will be made on July 2005 by the end of the project.
3 The systems analysis of the Nordic H₂ Energy

3.1 The Nordic Hydrogen Energy Model

During the project, a simplified technology based hydrogen energy model was created with linear programming method to analyse different hydrogen energy scenarios and pathways in the Nordic environment. The model includes hydrogen based technologies only, which makes it easy to use. The markets (i.e. H₂ demand, market prices of fuels and electricity, CO₂-tax, etc.) are specified by the user. The created model is a representation of the flows of energy (energy carriers) and technological alternatives in the hydrogen energy system. With the help of the model the analysis of least-cost strategies for achieving hydrogen energy and policy targets may be carried out. Annual costs are accumulated into the milestone years by linearisation and discounting, and the total cost (i.e. real cost) is minimised by using the linear programming method. The total cost includes all the investment and operating costs from the present to the final year of the scenario specified by the user. The energy and hydrogen balances of the model ensure that the demands of electricity, heat and transportation fuel will be covered. The necessary plant capacity to maintain these balances is obtained by investments to a new capacity. The representation of the Nordic hydrogen energy model is shown in the Figure 3.

The input of the model for different milestone years includes:

- Hydrogen energy demand for electricity, heat and transportation energy (% of the total demand)
- Division of the hydrogen demand between centralized and decentralized demands
- Market prices for fuels and electricity
- Cost data (investment, operating)
- Technical data (efficiencies, loss factors, life times, availability)
- Economical data (discount rate)
- Policy measures (investment subsidies, CO₂-tax).

Figure 3. Representation of the Nordic hydrogen energy systems model.
3.2 Description of the Nordic energy system and its future perspectives

The Nordic countries have a wide diversity of primary energy sources, which is shown in Figure 4. In electricity production, the share of hydropower is more than 55%. The share of wind power is about 2%, which is mainly produced in Denmark. In addition to renewable energy sources, Norway and Denmark have a considerable production of oil and natural gas. International electricity grids are well developed in the Nordic countries and allow for transmission over long distances. Denmark, Finland, Norway and Sweden form a common electricity market area with the Nord Pool power exchange. Connections of electricity also exist to Germany, Russia and Poland. The natural gas network is well developed only in Denmark. In Finland and Sweden, the network covers the southern part of the country. In Norway, onshore natural gas grid practically does not exist.

In the Nordic countries, industrial energy consumption is large due to high energy intensity in, for example, pulp and paper and metal industries. Because of cold climate, the share of space heating is high in overall energy consumption. However, the overall efficiency in energy production is high, since more than 80% of thermal power is produced in combined heat and power plants (CHP). Since 1990, total electricity consumption has risen by an average 1.2% annually (Swedish Energy Agency, 2003). The total energy demand in the Nordic region was estimated to grow about 7% from 2002 until 2030 in the Nordic region (Eurelectric 2002, EU 2004) as shown in the Figure 5. The highest increases were assumed in consumption of electricity (18%) and transportation fuels (12%) (Koljonen & Pursiheimo, 2004).

3.3 Input values for the scenario calculations

In energy production, the changes in the existing systems are very slow due to long life times of generating plants. Also, hydrogen as an energy carrier would compete with other sustainable energy systems. In the assessment of external scenarios, it is assumed that the role of hydrogen as an energy carrier would be minor in industry. Therefore, future hydrogen demand in the Nordic area is only divided into electricity generation, space heating and transport use. The share of hydrogen in transportation sector is assessed as in “big visions” by 2030. In the other two sectors, i.e. in stationary applications, it is assumed to be approximately half of the “big visions”. It is important to emphasize that the aim of these ambitious Nordic hydrogen visions is to set out
challenges and not to predict what may likely happen.

The technologies included in the scenario calculations were selected according to the result of the roadmap exercise. In the model, the \( \text{H}_2 \) demand is also divided into centralized and decentralized hydrogen demands (see figure 3). The shares in 2005-2030 were set according to the expert judgments to 60%-70% for centralized demand, 10%-15% for decentralized demand along natural gas pipeline and 20%-25% for decentralized demand without natural gas pipeline. The energy sources for hydrogen production were settled in the Vision Workshop, as discussed in chapter 2.

The detailed description of the technical and economical data including investment costs, operating costs, efficiencies, life times and availabilities are given in the final report of systems analysis (Koljonen et al. 2005). For the ‘base case’ calculations we have selected the discount ratio of 5%. All the cost data is based on 2003 euros.

The investment costs of fuel cells and electrolysis were assumed to be subsided in the scenarios E1 and P2. Renewable energy sources were also favoured in these scenarios due to fuel tax for natural gas. Natural gas price level follows the price forecast by International Energy Agency (IEA, 2002). The biomass prices are based on the estimates for forest residues in Finland including transportation cost for 100 km. It should be noted, that biomass is a local energy source and the price level may vary a lot between Nordic countries. For electricity, two price levels were assumed; spot market price and higher price level for electricity produced from renewable energy sources. The market price estimates of electricity are based on VTT’s calculations with stochastic dynamic market price model of the Nordic market area (Koljonen & Savolainen, 2004). Renewable electricity prices are based on the production cost expectations of off-shore wind power.

Table 1. Assumed fuel and electricity prices, investment supports and fuel taxes for the milestone years 2005, 2015 and 2030.

<table>
<thead>
<tr>
<th></th>
<th>Scenario B3</th>
<th>Scenario E1</th>
<th>Scenario P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas (2005/2015/2030), €/MWh</td>
<td>14,0/13,5/15,0</td>
<td>14,0/12,5/13,5(^1)</td>
<td>14,0/16,0/19,5</td>
</tr>
<tr>
<td>Biomass (2005/2015/2030), €/MWh</td>
<td>10/14/20</td>
<td>10/14/20</td>
<td>10/14/20</td>
</tr>
<tr>
<td>Investment subsidy (2005/2015/2030), %</td>
<td>0/0/0</td>
<td>50/40/0</td>
<td>50/40/0</td>
</tr>
<tr>
<td>Fuel tax (2005/2015/2030), €/MWh</td>
<td>8/0/0</td>
<td>8/9/10</td>
<td>8/9/10</td>
</tr>
</tbody>
</table>

\(^1\) IEA price forecast (IEA 2002)
3.4 Scenario results of the Nordic hydrogen energy system

Figure 6 shows the total costs for the three scenarios and the hydrogen shares assumed for transportation sector. For stationary applications, the hydrogen share is half of the shares presented in figure 6. Figure 7 shows the investment costs for hydrogen production, hydrogen infrastructure and for heat and power production. It should be noted that the selection of discount ratio has a remarkable effect on the total costs. For example, the decrease in discount ratio to 3% increased the total costs about 35% in 2020 and 60% in 2030. With the model assumptions, the investments in the hydrogen infrastructure seem to be the highest.

Table 2 shows the shares of steam reforming, steam reforming with carbon capture, electrolysis and biomass gasification. According to the result of the roadmap exercise, carbon capture would not be available before 2010. Table 2 shows also the shares of fuel cells and gas engines for combined heat and power production (CHP) and fuel cells for electricity production only.

Table 2. Hydrogen production (MW) and energy production (MW) with different technologies for the milestone years 2005, 2015 and 2030 for the scenarios B3, E1 and P2.

<table>
<thead>
<tr>
<th></th>
<th>Scenario B3</th>
<th>Scenario E1</th>
<th>Scenario P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam reforming</td>
<td>20/300/800</td>
<td>40/500/2000</td>
<td>40/1800/2200</td>
</tr>
<tr>
<td>(2005/2015/2030), MW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam reforming with</td>
<td>0/100/400</td>
<td>0/1000/7200</td>
<td>0/300/9300</td>
</tr>
<tr>
<td>CO₂ capture (2005/2015/2030), MW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis, MW</td>
<td>5/100/400</td>
<td>5/200/1100</td>
<td>5/300/1300</td>
</tr>
<tr>
<td>Biomass gasification,</td>
<td>30/400/1300</td>
<td>30/1400/4900</td>
<td>30/2100/4400</td>
</tr>
<tr>
<td>MW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHP fuel cell, MW</td>
<td>10/300/2100</td>
<td>10/700/5100</td>
<td>10/1200/6100</td>
</tr>
<tr>
<td>CHP gas engine, MW</td>
<td>4/90/0</td>
<td>4/60/200</td>
<td>4/80/200</td>
</tr>
<tr>
<td>Fuel cell, MW</td>
<td>3/90/200</td>
<td>3/60/500</td>
<td>3/90/600</td>
</tr>
</tbody>
</table>

Figure 6. Total costs (in million €) and hydrogen shares for the transportation sector.

Figure 7. Investment costs (in million €) in energy production, hydrogen production and hydrogen distribution.
To fulfil the “big visions” energy demand for hydrogen energy in the Nordic transport sector, about 0.5-2 million hydrogen vehicles would be needed in 2020 and about 1-4 million hydrogen vehicles in 2030. The number fuelling stations needed in 2020 is estimated to 500-2000 and in 2030 to 1000-4000, respectively. These scenarios for hydrogen supply per station are based on the assumption that 50% of the vehicles are ICE-powered and 50% are equipped with a fuel cell drive train (HyNet 2004). The number of passenger cars totaled 8.2 million in 2002 in the Nordic countries (Eurostat 2004) and the total number of road vehicles was 9.6 million, respectively. According to EU scenario (EU 2004), the annual percentual change in passenger and freight transport activity could be approximately 1-2%. This means that it is very unlikely that the number of hydrogen vehicles would reach our “big visions”.

4 Conclusions

In our work, the technical and economical potential of hydrogen society in the Nordic countries as well as the competitiveness of the hydrogen based systems were analysed with the help of the linear optimization method. Because hydrogen technology is a rapidly developing area, the most challenging task in the modelling work was assessing and gathering the data. Despite of huge amount of information found from the literature, many of the inputs have a great uncertainty, especially in the longer term. The scenario calculations indicate that the highest uncertainty is related to the energy losses of the whole hydrogen energy system. The selection of discount ratio has a remarkable effect on the total costs. Compared to the investments in the hydrogen production and stationary applications for energy production, the investments in the hydrogen infrastructure seem to be the highest. However, the investment costs of hydrogen infrastructure have high uncertainty also.

In our scenario calculations, biomass gasification and steam reforming seem to be the most competitive technologies for hydrogen production. The competitiveness of biomass gasification is greatly affected by biomass fuel price, which is a local energy source. Electrolysis seems to be competitive in decentralized systems, if the electricity price is low enough. In our scenario calculations, CHP fuel cells seem to be the most competitive in the long term for energy production.

With the scenario assumptions, the approximated Nordic market sizes in 2030 for the base three basic scenarios varied from 1000 M€ to 3000 M€ for hydrogen production, from 1000 to 4000 M€ for stationary applications and from 4000 M€ to 12 000 M€ for hydrogen transmission. In 2020, about 0.5-2 million hydrogen vehicles and in 2030 about 1-4 million hydrogen vehicles would be needed to fulfil the “big visions” for hydrogen energy in the Nordic transport sector. The number fuelling stations needed in 2020 was estimated to 500-2000 and in 2030 to 1000-4000 respectively.

The analysis of competitiveness of hydrogen systems in the Nordic environment compared to other sustainable energy applications would need more detailed and comprehensive systems analysis. This could be done with larger bottom-up systems models, like MARKAL or TIMES. However, these models need detailed regional information of the existing energy systems, which makes the input database very large. Also, the type of technical and economical data on hydrogen based technologies that were used in this study should be defined for the other competing future energy systems too. Compiling detailed technology roadmaps and systems analysis are challenging tasks for a technological area that is undergoing rapid development, especially when there is
an additional regulatory uncertainty caused by unpredictable political decisions. The foresight process offered good opportunities in identifying and validating data to the modelling work. This process can be further optimised by more detailed and comprehensive studies and analysis, which again should be validated by the key stakeholders.

5 REFERENCES


Malmö Hydrogen and CNG/Hydrogen filling station and Hythane bus project

Bengt Ridell Carl Bro Energikonsult AB, Sweden, 2005-04-15
bengt.ridell@carlbro.se

1. Background

The largest private utility company in Sweden, Sydkraft, with its head office in Malmö has a history of being in the forefront of the technologically development. Sydkraft belongs today to the E.ON group. Already in 1985 Sydkraft and the Municipality of Malmö started a long-term co-operation regarding conversion from diesel to CNG on the city buses. Now in the region Skåne more than 330 buses, 80 trucks and about 1000 cars are running on CNG and biogas. In 1995 the parties both implemented use of Electric Vehicles in their fleets as a part of a large EV demonstration project in the region. This quest for testing new alternative fuelled vehicles has continued and the latest step is now to test hydrogen mixed together with natural gas for local city buses.

Carl Bro Energikonsult AB has been an active partner in the project from first idea, design, project management, procurement, and start up of the filling station.
2. The hydrogen production plant and filling station,

The hydrogen plant and the filling station is situated at Nobelvägen 66 in Malmö and owned and operated by Sydkraft Gas AB. It started operation in September 2003. At the same site there are filling stations for CNG and also electrical vehicles.

The hydrogen is produced by electrolysis in direct connection to the filling station. The electricity is produced in a nearby windpower plant and distributed to the plant via the electrical grid.

The hydrogen plant including the production and filling station is delivered by Stuart Energy, Canada. The electrolyser unit is manufactured by Vandenborre Hydrogen Systems in Belgium, a subsidiary of Stuart Energy, Canada now owned by Hydrogenics ltd, Canada.

Technical data for the electrolyser as stated by the supplier,

- Capacity: 36 Nm$^3$H$_2$/h
- Power consumption electrolyser: 4,2 kWh/ Nm$^3$H$_2$
- Power consumption in total: 5,5 kWh/ Nm$^3$H$_2$
- Water consumption: 36 l/h
- Pressure from electrolyser H$_2$: 10 bar
- Power requirement: 210 kW
- Load area: 25 – 100 %

![Fig 1. Hydrogen storage pressure tanks](image1)

![Fig 2. Hydrogen storage](image2)

The above pictures show the compressed hydrogen storage at the site. The hydrogen storage is placed closed to the electrolyser unit. The pressure vessels are delivered by Dynatech, Canada.

- Pressure 393 bar
- Volume 4m$^3$
Fig 3. Dispenser hydrogen and mix of CNG/hydrogen

The dispenser is delivered by FTI, Canada it consists of two hoses one for pure hydrogen and the other for the mix of hydrogen and CNG. The mixture is done in the dispenser directly while filling the vehicle fuel tank.

The different fuelling options at the dispenser are,

- Hydrogen 350 bars
- Hydrogen 200 bars
- H2/CNG CNG with a blend of 8vol% hydrogen
- H2/CNG CNG with a blend of 20vol% hydrogen

The backgrounds to use these four fuelling options are

- Hydrogen 200 bar is a classic standard for delivery of bottled industrial hydrogen and several hydrogen demonstration vehicles are using 200 bar as pressure in the fuel tank.

- Hydrogen 350 bar is a new standard often used for fuel cell vehicles. DaimlerChrysler Evobus has specified 350 bar as onboard storage for the hydrogen fuel on their Citaro buses used in the CUTE and other similar projects. It is also the standard for DaimlerChrysler FCell fuel cell cars and several other modern demonstration vehicles using hydrogen as fuel.

- H2/CNG with a blend of 8vol% hydrogen; this lean mixture of hydrogen into the CNG is considered as CNG according to the specification of natural gas. The mixture can be used directly in the current CNG city buses without any modifications of the fuel system or engine set points or hardware.

- H2/CNG with a blend of 20vol% hydrogen; A larger portion of the fuel is produced locally and more environmental benefits can be achieved. This heavier mix of hydrogen into the CNG cannot be considered as natural gas. A modification of the engine set points for ignition and fuel injection is required. A comprehensive safety check of the fuel system of the buses has been performed.
3. The bus project, engine improvements

The background of the bus project to use a mixture of hydrogen and CNG are

- To use a locally produced fuel
- To improve the efficiency and the operation of the engines
- To decrease emissions, both local emissions and CO$_2$

Two buses of the local bus fleet have tested CNG mixed with 8 %$_{vol}$ of hydrogen as fuel without any modifications of the lean-burn CNG engines for more than one year. The Lund Institute of Technology at Lund University, Sweden, has confirmed significant improvements in fuel efficiency, more stable operation of the engine and reduction of emissions by performing bench testing of the engines. Measurements of efficiency, emissions, combustion variations, knocking etc have been performed during different conditions.

![Efficiency 2000 rpm](image)

**Fig 4. Brake efficiency 8$_{vol}$ % Hydrogen**

It is reasonable to expect that the brake thermal efficiency could increase with hydrogen mixed into the CNG fuel as compared to pure natural gas since the combustion duration is reduced. With reduced combustion duration the effective expansion ratio increases and more work can be extracted from the gas. This increase in efficiency is likely to be the highest where the combustion duration is long with natural gas, i.e. at lean conditions. The Volvo TG100 engine used in the local city is lean burning engine and can thus profit from the use of the mixture of hydrogen and CNG as fuel.

The increase in efficiency together with the reduction of the carbon content in the decrease the emissions of CO$_2$ substantially fuel when the use of hydrogen as a fuel additive.
A mix of hydrogen into the natural gas creates a faster combustion and thus more efficient combustion. Lower emissions of HC and CO are then achieved, as the combustion is more efficient. The higher combustion temperature can though increase the NOx emissions. This can be avoided by using a higher air/fuel ratio and/or less spark advance.

The flame speed of hydrogen is much higher than that of hydrocarbon fuels. Adding hydrogen to natural gas is thus likely to increase the flame speed of the charge. This could be used to extend the lean limit of the natural gas engine to air/fuel rates ratios where pure natural gas provides insufficient burn rate for stable combustion.1/
Summary of the conclusion with the measurements in a laboratory with a mixture of 8 % vol into the CNG using a Volvo TG100 engine.

- Higher efficiency
- More stable combustion, due to a faster combustion (less cycle to cycle variations)
- A slight increase in power
- Lower HC and CO emissions because of higher combustion efficiency
- Higher or similar NOx emissions (with no changes applied to fueling or spark)
- Slightly higher knock tendency

Further test with a 20% hydrogen mix in the CNG have been performed in the laboratory. These tests show significant improvements. The reduced combustion duration increases the efficiency significantly and enables the reduction of NOx emissions by using a higher air/flow ratio combined with optimised ignition timing. The reduction of CO₂- emissions is substantial.

The above figures show results from engine tests with 20% vol hydrogen mixed with CNG. It shows the trade-off between HC and NOx emissions when different ignition angels have been used. The different measurements shown represent different air/fuel ratios. Extreme air/fuel ratios can lead to other problems like instable engines or too high knock tendency etc.

Furthermore is also the other the harmful emissions significantly decreased as the carbon content of the fuel has decreased with the heavier blending of hydrogen in the fuel. This is especially significant for the reduction of CO₂ emissions.

4. The status of the bus and vehicles operation

The operation with the mixture of 8 vol % hydrogen in the natural gas started in September 2003. Two city buses have used the Hythane fuel with 8 % hydrogen. This has been done without any modifications of the engines. The buses could then also use CNG as fuel if needed.
The heavier mixture with 20 vol % hydrogen in the CNG has been used since the beginning of year 2005. This has required modifications of the mapping of the engine both for ignition and the air/fuel ratio. Connecting a PC for adjustments of the control system of the bus engine did the necessary modifications. There have not been any hardware modifications done. A comprehensive study of all components regarding safety has been performed by the engine manufacture.

The long-term vision is to use a mixture of hydrogen and CNG in all the city buses.

An emissions test on the engines on buses in operation will be performed later this year. The test will be made on a certain road where equal conditions can be obtained during the test period.

Several passenger cars have tested the low-grade 8 vol % Hythane fuel with good results. There is a foreseen project to test 10 passenger cars including taxis and other service vehicles running on Hythane for a longer test period.

A few hydrogen vehicles have visited the filling station but there are not yet any demonstration projects for vehicles running on pure hydrogen.
References:


2. Hydrogen additive for improved lean burning capability of slow and fast burning natural gas combustion chambers, Per Tunestål, Magnus Christensen, Patrik Einewall, Tobias Andersson, Bengt Johansson, Lunds Institute of Technology, department of Heat and Power Engineering, Lund, Sweden, Society of Automotive Engineers, Inc, USA

Session 4 – Hydrogen – Technological Aspects

Chairman: Thorsteinn I. Sigfusson, University of Iceland
A vision for the intermediate step towards the hydrogen society

By Niels Henriksen, Charles Nielsen and Flemming Nissen, Elsam A/S,
and Jan Larsen, Elsam Engineering A/S

Abstract

The hydrogen society is an important issue in the public debate. The hydrogen society is regarded as being the solution to future problems with security of supply especially within the transportation industry, and as being the solution to the CO₂ problem, and not least as being able to create jobs in the western world and thereby compensate for the jobs that move to low-wage countries.

However, many problems have to be solved before a true hydrogen society becomes a reality. To solve these problems within a short period of time, intermediate steps have to be taken.

This paper presents an Elsam vision of a hydrogen society. The vision comprises an integrated production of ethanol and methanol from biomass, CO₂, electrolytically produced hydrogen and natural gas.

Since the vision is technically and financially feasible and the first steps can be based on known technology, the vision can be realised, and the desired effects can be achieved within a foreseeable time. Furthermore, the vision will provide possibilities for absorbing relatively large quantities of wind and solar energy into the power system.

Background

This vision is based on three main issues in the western world:

- Oil demand and resources
- Climate change
- Employment

Oil and energy demands have increased over time and especially in the recent years due to the large economic growth in China.
According to the Association for the Study of Peak Oil & Gas exploration and findings of new oil fields have been at a very low level for several years. As shown in figure 1 new discoveries peaked in the 60’ies. At the same time oil consumption has increased steadily over the last 60 years and the increase is expected to continue for decades. Until now, production has been able to follow the increase in consumption.

New oil fields will also be discovered in the future, but will most probably be located in areas with harsh climate, sensitive environment, deep sea or in political instable regions. Production cost will be higher, and as the oil price is determined by the highest marginal cost at a certain demand – oil prices must be expected to increase at constant demand level. Further price climbing could be expected due to the increase in demand.

Oil could be substituted by synthetic fuel based on fossil fuels like natural gas and coal. But increased consumption of these resources will put a price pressure on both natural gas and coal. The break-even level for these conversion technologies is considered to be less than the actual oil price. A break-even price on coal will be in the range 25-31 USD/bbl (Williams).

Climate change is also a parameter to be considered either you a believer of the green house theory or the cosmic particle/cloud theory. Politics based on the CO₂ theory will lead to higher fossil prices due to quotas put on the CO₂ emissions. The consequence of the other theory is that the global temperature will depend on natural variations mainly the solar activity. History shows that temperatures are cycling. In England there were cold periods in 1500, 1620, 1700, 1810 og 1890 – the next cold period could be coming soon. (Calder). A global temperature fall will lead to a much higher demand for fossil fuel for heating.

The high growth in China has increased worries in the western world about the competitiveness of the industry in this part. Europe has to find alternatives to the export of jobs to Asia. Europe has some advantages compared to other parts of the world. Energy and raw material efficiency are high and experience with renewable energy is also high. Europe might have a competitive advantage in these areas.
Alternative fuels

If the theory of peak oil is accepted this will lead to an increasing price trend for oil over the next decades. Of course there will be some economical crises where oil prices will drop back to old levels due to periodically reduced consumption. An increasing price trend for oil will make alternatives for the transportation sector more attractive. Alternatives are:

- Compressed gaseous fuels (natural gas possibly mixed with hydrogen)
- Synthetic liquid fuels (made from gas, coal and renewable energy)
- Plug-in hybrid cars (electricity and liquid fuel)

The alternatives should be viewed from the need for capital investments in production and infrastructure, the price correlation with oil, the resources of the alternatives, and the political stability of the regions providing the alternatives and finally Europe’s own resources and competence.

Compressed gaseous fuels

Our opinion is that compressed gaseous fuels will never be a widespread global solution due to large infrastructure investments and access to a natural gas pipeline system. Compressed gas solutions will probably be attractive in Europe as the gas infrastructure to a large extent is already available. The problem with gas as a resource for transportation in Europe is capacity limitations and increased dependence of natural gas from Russia and the Middle East.

Mixing with hydrogen will reduce the natural gas dependence but will increase the infrastructure capacity needs due to the higher volume of hydrogen per energy content.

Synthetic liquid fuels

The absolute advantage by synthetic liquid fuels is that the global infrastructure for liquid fuels could be used. Liquid fuels are available at the most remote areas of the earth.

One of the problems with liquid fuels is that you can only allow very few qualities of fuel. Typically diesel and 2-3 octane qualities of petrol where one of the qualities could be an alcohol based quality.

Liquid fuel could be Fischer Tropsch fuel, which can be reformed to petrol and diesel quality or it could be alcohols or alcohol/petrol blends. The alcohols are ethanol or methanol. Ethanol is already widespread used and is typically blended with gasoline to a 5% solution. Methanol is another alternative but is mainly used in auto sport vehicles. Methanol is the primary fuel choice for fuel cells in transportable equipment. If fuel cells finds the way to the automotive industry methanol must be regarded as a good fuel candidate. Methanol is easily transported compared to hydrogen and it is easily reformed to hydrogen at rather low temperatures (200-250°C).

Methanol reforming combined with high-temperature PEM cells (ref 3) has the advantage that heat recovered from the fuel cell reaction equals the energy input and temperature for methanol reforming.

Fischer Tropsch fuels (FT fuels) are normally based on fossil fuels like coal, gas or gasified biomass. Many of the gas resources intended for FT fuel production are located
in the same oil producing countries that today are considered more or less political
instable.

An alternative where resources used are based on renewable energy from Europe would
have beneficial effects on the security of supply and at the same time provide
employment to both well-educated people and less educated people. Alcohol based
liquid fuels have more advantages than disadvantages compared to FT fuels.

Advantages:
- Investment cost for production plants are lower. (kilde ..)
- Motor efficiency is higher.
- Hydrogen consumption is lower in synthesising the fuel especially for methanol
  (se reactions below). This is an important issue if the hydrogen source is made
  of renewable electricity; wind, photovoltaics or wave energy.
- Alcohols are more adaptable to future fuel cell technologies for vehicles.
- Alcohols are easily metabolised in nature.

Disadvantages:
- The energy content per litre of fuel is lower.

We find the advantages so convincing that we have formulated a vision for an integrated
production of ethanol and methanol based on renewable energy sources in a process
integrated with heat and power production. The vision is named REtrol, which stands for
Renewable Energy in petrol.

Plug-in hybrid cars on electricity

This concept encompasses cars operating on a rechargeable battery in combination with
another fuel typical gasoline. Today hybrid cars, which recharge the battery with the
combustion engine, are sold worldwide and Toyota Prius was the number one selling
hybrid car in 2004.

Plug-in hybrid cars, which use the electricity net, are not yet on the market, but will
probably soon be seen on the market. The plug-in hybrid car can be recharged during
long-stay parking. Battery driving is mainly used for city driving and the combustion
engine takes over when the battery is low.

Hybrid cars often recover brake energy and use it to recharge the battery. In this way the
total energy consumption could be lowered especially when driving in cities.

Plug-in hybrid cars would be beneficial in an electricity market with a lot of varying
renewable energy productions.

Combinations

A way to overcome the problems with lacking infrastructure is introduction of fuel
flexible vehicles or bi-fuel vehicles.
Ford and other car manufacturers have large selections of fuel flexible vehicles. Ford has sold hundreds of thousands of fuel flexible vehicles to the American market. Fuel flexible vehicles are typically able to drive on arbitrary compositions of petrol and alcohol (methanol or ethanol). Ethanol is the actual choice, but it would be possible to use methanol or methanol/ethanol blends as the alcohol part.

Bi-fuel vehicles are able to drive on both compressed gas and liquid fuels. The picture shows the back-end of Volvo bi-fuel vehicle. Volvo has sold 12,000 bi-fuel cars since the beginning of 1991. The largest bi-fuel market for Volvo is Sweden, Germany, Switzerland, Austria and Italy. In Germany three gas filling stations open every week. Italy has approximately 400,000 gas vehicles on the road and growth in Switzerland is high – 62% for gas driven vehicles and 80% for filling stations.

The ideal vehicle would be a hybrid bi-fuel car operating on electricity and liquid fuel, where the liquid fuel is fuel flexible.

The REtrol vision

Ethanol is produced from ligno-cellulosic waste materials from agriculture, forestry, households and manufacturing industries.

The lignocellulosic material is pre-treated in a continuous hydrolysing process and decomposed to fermentable carbohydrates in advanced enzymatic processes. Solid and liquid left overs from this process are utilised as fuel in combustion or in gasification processes. The fermentation produces equal amounts of CO\(_2\) and ethanol. Instead of emitting the CO\(_2\) - this valuable renewable carbon source is synthesised in to methanol with hydrogen from renewable sources. As an alternative methanol can be synthesis from a traditional synthesis gas (CO and H\(_2\)) made from gasification of biomass and waste possibly in combination with coal.
The vision tries to make a simplified imitation of the natural carbon cycle. This artificial imitation of the carbon cycle is shown in the figure below.

Fig. 4: The synthetic carbon cycle

The products are non-food renewable energy products (RE-ethanol and RE-methanol), which are expected to have a higher sales value than fossil equivalents due to the public interest in protecting and/or subsidising renewable energy markets.

**The REtrol production processes**

The overall process diagram for the vision is shown in figure 5.

Fig. 5: Graphical presentation of the REtrol vision

**Ethanol (C₂H₅OH)**

Ethanol is made by biological processes from biomass. Bio-ethanol production from polysaccharide containing biomasses can be divided into four steps:

- pre-treatment
- hydrolysis of the polysaccharides into fermentable carbohydrates
- fermentation of the carbohydrates
- destillation
Several pre-treatment techniques are known. For cereals and grains, this pre-treatment may be in the form of a simple dry milling in order to render the surfaces accessible, but for lignocellulosic biomasses (typical straw with the constituents cellulose, hemicellulose and lignin) thermal and/or chemical processes are needed as well. A polysaccharide containing biomass consisting of e.g. refined starch does not require pre-treatment methods prior to enzymatical processing. Pre-treatment processes may be based on acidic hydrolysis, steam explosion, oxidation, extraction with alkali or ethanol etc. A common feature of the pre-treatment techniques is that combined with the action of possible added reactants they take advantage of the softening and loosening of plant materials that occurs at temperatures above 100°C.

Following the pre-treatment, the next step in utilisation of polysaccharide containing biomasses for production of bio-ethanol or other biochemicals is hydrolysis of the liberated starch, cellulose and hemicellulose into fermentable sugars. If done enzymatically this requires a large number of different enzymes with different modes of action. The enzymes can be added externally or provided by microorganisms growing on the biomass.

Cellulose is hydrolysed into glucose by the carbohydrolytic cellulases and the different sugars in hemicellulose are liberated by the hemicellulases. In combination with pre-treatment and enzymatic hydrolysis of lignocellulosic biomasses, it has been found that the use of oxidative enzymes can have a positive effect on the overall hydrolysis as well as the viability of the microorganisms employed for e.g. subsequent fermentation.

Fermentation of the liberated sugars from hydrolysis processes is carried out using yeast or more advanced thermophilic bacteria. It is important that pre-treatment and hydrolysis process do not produce inhibitors for the fermentation that the bacteria are immune to the by-products.

The final step in the process is distillation where the ethanol is concentrated from a low percentage solution to a concentrated liquid suitable for fuel.

The distillation and the pre-treatment processes are very energy consuming and integration into a power plant lowers investment and energy cost. In a power steam at the desired temperatures are available and a lot of low value heat can be extracted from the power plant process and be used in the energy consuming distillation process. Another advantage by power plant integration is the possibility to use waste products developed during the various processes in the combustion.

Elsam in-house studies indicate that production cost can be lowered by 10-15 % compared to a stand-alone plant.

**Methanol (CH₃OH)**

Methanol is the smallest alcohol and is made by catalytic synthesis from a synthesis gas made of CO, CO₂ and hydrogen (H₂), according to reactions below:

\[
\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH} \\
\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \\
\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 2\text{H}_2
\]

The most optimal way to methanol is a hydrogenation of CO, which only requires two
molecules of hydrogen.

The normal way to produce natural gas is through reforming of natural gas by combining various reforming processes:

\[
\begin{align*}
\text{CH}_4 + \text{H}_2\text{O} & \rightarrow \text{CO} + 4\text{H}_2 \quad \text{(steam reforming)} \\
\text{CH}_4 + \frac{1}{2}\text{O}_2 & \rightarrow \text{CO} + 2\text{H}_2 \quad \text{(partial oxygenation)} \\
\text{CH}_4 + \text{CO}_2 & \rightarrow 2\text{CO} + 2\text{H}_2 \quad \text{(dry reforming)}
\end{align*}
\]

The reforming processes are normally carried out simultaneously in an autothermal reformer. One of the global energy strategies is to transform the so-called stranded natural gas (natural gas resources in remote areas far from pipelines) to methanol.

Another strategy is to produce methanol of renewable resources, which requires production of synthesis by gasification of biomass and waste or by hydrogen production and CO\(_2\), where CO\(_2\) is supplied from the ethanol fermentation process or recycled CO\(_2\).

The electricity consuming processes as the electrolytical hydrogen production and gas compression are used to balance the electricity market. There is a special need to balance markets with high amounts of variable renewable electricity production. The intention is to avoid electricity consumption during peak hours and use maximum electricity production for hydrogen production and gas compression. During the peak hours in the electricity market the methanol production is running at minimum load using stored reactants or natural gas.

**Technology state of art and technology challenges**

Both ethanol and methanol are produced today with conventional technology. The vision operates with developments that will be add-ons to well-known and proven technologies.

The ethanol production use the logistics of large scale biomass handling, which have been introduced and used on power stations for the last 2 decades or more.

The ethanol production is first introduced as conventional production integrated in power plants to avoid too many uncertainties at a time. A minor lignocellulosic pre-treatment and hydrolysis process will be added to the conventional process.

Development is concentrated on making the pre-treatment faster and more efficient and on introducing thermophile bacteria, which allow continuous stripping of the alcohol.

The methanol production will also be developed on the basis of proven technologies. The simplest way to make methanol is a combination of CO\(_2\) from fermentation and electrolysis. The balance is shown in the figure below.

For the calculation the following production profile has been used:

- Methanol load is 100% in 6,500 hours, 20% load in 1,590 hours and shut down is 4 weeks and 670 hours.
- Methanol load at 20% is when electricity markets peak. Gas is taken from gas storage tanks. Storage capacity is 12 hours at 20% load.
With electricity cost for electrolysis at 30 €/MWh (market price) or 60 €/MWh (renewable electricity price) the contribution to the methanol price is 0.27 €/kg and 0.54€/MWh. The process cost for CO₂ is estimated to 13 €/tons or 0.02 €/kg methanol.

Spared emission cost for reduced CO₂ emissions from fossil petrol is estimated to 13€/ton or 0.06 €/kg methanol. CO₂ emission from methanol is renewable and emission cost is 0 €/kg. The estimated capital cost is around 0.12€/kg methanol and operation and maintenance amounts to 0.02€/kg methanol.

The resulting renewable methanol price ex production facility and without taxes is 0.36 €/kg = 0.58€/l petrol equivalent (electricity and market price) or 0.64 €/kg = 1.02€/l petrol equivalent (renewable electricity price). The price must be compared to a market price ex refinery at approximately 0.38 €/l petrol. The price for RE-methanol is to be considered high, and it is very sensitive to variations in electricity prices, but in this regard it must be borne in mind that with in other areas of the energy sector society is willing to pay a high price for renewable energy products, which could very well by 3-4 times the market price.

Furthermore, the use of methanol opens up the possibility of increasing the efficiency in combustion engines or in time convert to fuel cell engines. This could be the combination of steam reforming and high temperature PEM fuel cell.

Electrolysis is a costly process and there is a need to focus on research and development in the following areas:
- Lower capital cost
- Higher hydrogen efficiency
- Use of oxygen
- Integration with other processes.
Market state of the art and market challenges

As regards introducing methanol on the market there is a need for incentives as the use for energy purposes is relatively limited.

It would be desirable to achieve acceptance for admixture of small amounts of methanol in petrol. At the same time it is desirable with economic incentives for introducing RE-based methanol on the fuel market.

It would also be desirable if methanol technologies were promoted, eg methanol based high efficiency combustion engines, methanol based fuel cell technologies and kit for converting existing technologies.

Conclusion

An increase in demand for fossil fuels is to be expected to continue over the next decades at the same time, as discovery of new resources will not be able to follow the increase in demand. Thus the increasing price trend will continue over the next decades, even though there will be fall in prices at times.

Therefore it is necessary with alternatives and especially alternatives using local resources over imported resources.

Methanol and ethanol based on renewable energy sources is one of the possibilities the western countries can implement on a relatively short term, and where the technologies are present for large-scale production but also possibility for new technological advances.

Citations


Volvo: http://www.volvocars.com/AboutVolvo/Environment/AlternativeFuels/BiFuel/

Williams, Robert H. and Eric D. Larson. A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal.
http://www.ieiglobal.org/ESDVol7No4/dcliversussicl.pdf
Rational design of new materials for energy storage

Tejs Vegge*, Anders Andreasen and Allan S. Pedersen
Materials Research Department, Risø National Laboratory
Frederiksborgvej 399, DK-4000 Roskilde, Denmark

Abstract
Diversity of energy supply has become a mantra in the industrialized countries over the last years, which has only become louder by the recent surge in oil prices. Hydrogen is widely considered as a prominent energy carrier for the future, particularly for use in the transport sector; although a suitable storage medium still remains to be developed. Synthesis of novel storage materials is often time-consuming and expensive, but recent advances in theoretical modeling and improved insight at the nano-scale can provide a shortcut.

Here, we illustrate the potential and possibilities of state-of-the-art in experimental and theoretical methods with particular emphasis on the obtainable synergy of an integrated approach. At the Materials Research Department (MRD) at Risø National Laboratory we combine density-functional calculations with in situ X-ray diffraction, synchrotron/neutron radiation, and advanced materials testing in an attempt to expedite the design and development of new materials. We focus primarily on obtaining improved nano-scale and structural knowledge to guide our search, as exemplified in this paper.

1 Introduction
The limited supply of fossil fuels is a growing global concern, in particular considering recent oil-consumption forecasts for Asia, where, e.g. the sale of passenger cars in China has tripled from 2001-2003. In light of the volatile and soaring oil prices, the industrialized countries have placed intense research efforts on creating a security of supply relying on alternative energy carriers for the – not so distant – future.

One alternative energy carrier which currently receives much attention is hydrogen, since a potential “hydrogen based society” would also deal with key environmental concerns, i.e. big city pollution and CO₂ emissions. Over the last couple of years, hydrogen research has been strongly supported in the USA, Japan and EU, all aiming at taking the lead in the potential industrial growth and labor opportunities. An actual “hydrogen technology” is, however, still under development, since key scientific problems remain to be solved. Although hydrogen production and distribution hold main concerns, it is generally believed that the show-stopper for a hydrogen economy is the automotive industry, where the development of a light-weight, safe and financially competitive on-

* Corresponding author: tejs.vegge@risoe.dk
board energy storage system is required as an alternative to gasoline. Over the last decade it has become increasingly apparent that the macroscopic behavior of materials is often controlled by mechanisms at the nanometer scale, and even well characterized materials have been found to display radically different behavior in this regime, e.g. the catalytic effect of nanometer gold particles on CO oxidation. The possibility of designing specific materials properties by nanoscale engineering is rapidly becoming a realistic opportunity; in particular due to a combination of wide access to super computers and accurate theoretical methods, experimental techniques becoming able to perform in situ analysis at the nanometer scale, and novel production techniques like nanolithography. The prospects of obtaining synergy by utilizing this variety of techniques are particularly interesting in the development of new energy storage materials, where synthesis and characterization are often very expensive and time consuming, and analysis of rate limiting processes like hydrogen dissociation and diffusion as well as thermodynamic and structural stability analysis are well suited for an unbiased theoretical investigation.

In this paper we illustrate the level of detailed information which can be obtained using state-of-the-art in theoretical and experimental techniques, spanning density-functional theory to X-rays and neutron scattering. The focus is on complex hydrides and their structural and kinetic properties, particularly areas, where the materials design process can be aided significantly by the synergy of an integrated theoretical-experimental approach.

2 New energy storage materials

The development of new materials for energy storage is paramount if a viable alternative to oil and gasoline is to be available in the near future. The American Department of Energy (DOE) has set a target of 9.5 wt% hydrogen for the storage capacity by 2015; this target renders conventional methods like metal hydrides, liquid and pressurized hydrogen practically useless. New classes of storage materials are, however, showing promise, and some of the primary candidates are briefly outlined in the following.

2.1 Complex hydrides

Following the 1997 discovery by Bogdanovic and Schwikardi of reversible ab- and desorption of hydrogen at near ambient conditions in titanium doped sodium alanate, NaAlH₄ (a material otherwise considered useless for reversible hydrogen storage), the so-called complex hydrides have dominated the international research in solid state hydrogen storage. The theoretical storage capacity of complex hydrides is very high (≤ 20 wt%), potentially an order of magnitude higher than the conventional metal hydrides operating at ambient conditions. Only few of these complex materials have yet been produced due to the complexity of developing new synthesis procedures, and as of now, no physical explanation for the role of the essential “catalytic additives” has been provided.

2.2 Other chemical hydrides

As an alternative to direct and reversible hydrogen storage in complex hydrides, other types of chemically bonded hydrogen storage systems are also investigated. Irreversible storage in sodium borohydride, NaBH₄, yielding 6.7 wt% hydrogen is already possible, but recycling the produced NaBO₂ into NaBH₄ is too expensive for commercial use.
Similarly for ammonia, either in liquid form or stored in amine-borane type complexes \( \text{NH}_3\text{BH}_4 \) (24.5 wt% hydrogen), \( \text{NH}_3\text{BH}_3 \), \( \text{LiBN}_2\text{H}_6 \) or salts.\(^7\) In solid form, such materials expand substantially upon loading, making e.g. 3D X-ray tomography an excellent method of analysis (see section 4.2).

### 2.3 Metal-Organic-Frameworks and Clathrates

The classes of materials described above rely on chemically bonded hydrogen, whereas other materials rely on weak physisorption of hydrogen by van der Waals forces in combination with a structural confinement.

The experimental discovery of high hydrogen storage capacity (4.5 wt% at 78K) in a Metal-Organic-Framework (MOF)\(^8\) has attracted much attention in the hydride community, and recently a new kinetically limited hydrogen storage mechanism was discovered in another MOF,\(^9\) where the potential of loading the medium under high hydrogen pressure, but retaining it at a substantially lower pressure was shown. A dynamical “window opening” effect is expected to control the hydrogen release, i.e. a kinetically limited hydrogen storage media – as opposed to the illusive optimal thermodynamic stability.

Similar storage potential was recently shown in clathrate hydrates of hydrogen, where the addition of THF increases the storage capacity at ~120 bars to 4 wt%.\(^{10}\)

### 3 Theoretical methods

The applicability of theoretical methods as a tool to help understand and design materials has grown dramatically over the last years. Large super computers based on “off-the shelf” components and more efficient software has made it possible to take the leap from atomistic modeling to the more accurate and unbiased first principles or ab initio calculations, even when treating highly complex materials problems.

#### 3.1 Density functional theory

The cornerstone of the theoretical work performed in the group is the density functional theory (DFT) pseudopotential plane-wave code Dacapo\(^{11}\) developed at the Centre for Atomic-scale Materials Physics (CAMP)\(^\dagger\). The code enables accurate determination of ground state structures and energies, which are essential for the determination of, e.g. formation energies. The DFT calculations are often performed in combination with other methods and techniques (see below), in order to reveal detailed structural and kinetic information about the energy storage materials.

#### 3.2 Path techniques

To calculate activation barriers for molecular dissociation or atomic diffusion processes, a path technique known as the nudged elastic band (NEB)\(^{12}\) method enables us to determine the minimum energy path and corresponding transition states. The method is primarily used to locate the transition state - and determine the corresponding energy - between two local energy minima. This is done by creating a series of complete replica of the system, typically 5-20 “images”, which are coupled by artificial spring forces; the component of the spring forces parallel to the path and the orthogonal forces from the

\(^\dagger\) Department of Physics, Technical University of Denmark (DTU).
potential are then minimized, converging toward the minimum energy path. This technique is an important tool in the analysis and potential optimization of reaction rates.

### 3.3 Transition state theory

Using the ground state energy differences between the initial and the transition state, as determined by a NEB calculation, it is possible to determine the rate of the given process using transition state theory (TST). In the harmonic approximation to TST, the problem is reduced to an Arrhenius expression, where the prefactor is determined by the vibrational modes of the initial and transition state, respectively, and the activation energy is the ground state energy difference. The vibrational frequencies can be determined using Dacapo and it is thus possible to analyze problems like locating the rate-limiting step for interactions between hydrogen and metals, as shown for the magnesium-hydrogen system and other complex rate problems in materials science.

### 3.4 Structural stability and prediction

Due to the time-scale of developing new synthesis procedures for complex hydrides and the difficulties of structural characterization, the ability to investigate the thermodynamic stability of a given materials combination theoretically is vital in this type of materials design.

The PHONON software package code relies on the *direct method* to calculate phonon dispersion curves and density spectra on the basis of ab initio calculations. The code enables the accurate determination of the stability of crystal structures at finite temperatures. Furthermore, analyzing the imaginary modes in phonon spectra of unstable (related) crystal structures it is possible to “create” a neighboring stable structure. In situations where the initial structures have too many negative modes, thermal annealing simulations using ab initio MD can be performed.

With these methods, the structural stability and thermodynamics of the complex storage materials can thus be calculated – even for materials not yet synthesized. We have recently illustrated the potential of this approach by predicting the existence of a new high temperature phase for the complex hydride lithium borohydride, LiBH₄, and simultaneously rendering an explanation to existing experimental data.

### 3.5 Nano scale properties

The hydrogen ab- and desorption in complex hydrides is found to depend strongly on the particle size of the storage medium, although the physical explanation remains to be established (see section 5.2). Investigations of the shape and properties of such nano sized particles can therefore reveal detailed information about catalytic bonding site and hydrogen desorption pathways, etc. DFT calculations of surface energies can be used to determine the equilibrium structures of such particles using a Wulff construction, as we have recently done for NaAlH₄ (see Figure 1).

*Figure 1* The equilibrium Wulff shape of a NaAlH₄ nano-particle, the dominant light blue facet is (001), but the presence of several other facets is also seen.
3.6 Charge analysis

The reactivity of catalytic complexes or particles on a complex hydride is expected to be directly linked to the charge of the catalytic component.\textsuperscript{20} The charge on the component and its dependence on the local atomic configuration can be analyzed theoretically using Wannier orbitals.\textsuperscript{21} This can be illustrated using doped NaAlH\textsubscript{4} as an example, where the best known “catalyst” (reacts with NaAlH\textsubscript{4} in some undisclosed way) is TiCl\textsubscript{3}. The Wannier orbitals and hence the charge on the Ti atom depends strongly on the local configuration, as shown in Figure 2. By summarizing the local Wannier orbitals, the charge on the Ti atom can then be analyzed in different configurations, thereby revealing if e.g. Na-vacancies are formed as a consequence of NaCl formation.

*Figure 2 An electronic Wannier d-type orbital (red) on a titanium doped NaAlH\textsubscript{4} (110) surface (Ti is under the orbital). The green atoms are Al, blue are Na, and white are H.\textsuperscript{22}*

4 Experimental methods

The in-house experimental facilities at the Materials Research Department at Risø National Laboratory provide different production techniques and several methods of analysis; these methods are supplemented by the access to international synchrotrons and neutron sources.

4.1 Synthesis

The samples can be produced either directly in a high energy ball mill, which is the predominant production/treatment technique due to the substantial improvements observed for the hydrogen ab- and desorption with decreasing grain size\textsuperscript{23} of the material and the possibility of doing mechanical alloying.\textsuperscript{24} Performing sample pre-treatment in an Edmund Buhler Arc melting system, it is also possible to create alloy compositions, which are difficult to access directly via mechanical alloying or conventional melting.

4.2 X-ray diffraction and tomography

X-ray powder diffraction (XRPD) is a powerful technique for investigations of structural and chemical details of crystalline materials both quantitatively and qualitatively, e.g. crystal structure, phase composition, crystallite size, etc. (see Figure 3). The department has a STOE X-ray tube powder diffractometer for *ex situ* studies and access to a Rigaku rotating X-ray anode for *in situ* studies. Applying small angle X-ray scattering (SAXS) nano-meter scale information about e.g. distribution of catalytic particles can be provided in extension to the atomic scale information from XRPD.

*Figure 3 XRPD pattern of LiAlH\textsubscript{4} before and after dehydrogenation.*
In collaboration with Center for Fundamental Research on Metal Structures in Four Dimensions (MRD, Risø), efforts are made to build a system, which can also be used to gain detailed 3D insight into hydrogen storage materials during ab- and desorption. High energy X-rays provide comprehensive 3D information of mm-sized specimens. The 4D Center has developed a unique 3DXRD microscope, positioned at the European Synchrotron Radiation Facility (ESRF), which enables characterization of the position, shape, orientation and stress state of the embedded grains.\textsuperscript{25,26} The change in grain morphology can be followed with a resolution of \( \approx 5 \) \( \mu \)m. Such measurements can be complemented by state-of-the-art tomography at Paul Scherrer Institute (PSI) and ESRF. Here, the density changes can be determined in 3D with a spatial resolution of \( \approx 1 \) \( \mu \)m\textsuperscript{‡} and a time resolution of 2 min.\textsuperscript{27}

### 4.3 Microscopy (SEM and TEM)

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used to gain detailed information about particle shapes and behavior before and after hydrogenation. In Figure 4, a SEM image of as-received NaAlH\(_4\) powder is shown, and the particles are seen to display characteristic shapes. Analysis by Energy Dispersive X-ray spectroscopy (EDX) reveals that both NaAlH\(_4\) and LiAlH\(_4\) powders are highly sensitive to oxygen contamination.

*Figure 4 Scanning electron microscopy (SEM) image of as-received NaAlH\(_4\) powder.*

### 4.4 Neutrons

Neutrons are ideally suited to characterize materials consisting of light elements, in particular hydrogen, due to a large scattering cross section. Neutron scattering can be used to obtain \( i ) \) detailed structural information by diffraction from coherent scattering, e.g. the location of H-atoms in a metal lattice, and \( ii ) \) information about dynamics from incoherent scattering, e.g. diffusion (Figure 5) and vibration.

*Figure 5 QENS data for NaAlH\(_4\) recorded for a Q-value of 2.15 Å\(^{-1}\) at \( T=150^\circ \text{C} \).*

We have access to the neutron scattering facilities at PSI, which can provide valuable information otherwise not accessible from X-ray scattering experiments.

\( \dagger \) See http://www.esrf.fr
4.5 Testing

In order to quantitatively evaluate the hydrogen storage capacity (uptake/release), hydrogenation/dehydrogenation kinetics, and thermodynamic properties, we use a Sartorius high-pressure microbalance operating at a range from vacuum to 50 bar hydrogen, and from RT to 500°C. The advantage of the instrument is the high precision direct gravimetric determination of hydrogen uptake/release. The drawback is that handling of materials without exposure to the atmosphere before and after experiments is difficult. To overcome this problem another instrument has been built which has a detachable reactor allowing materials handling (loading/unloading) to be performed in a glove box under a protected atmosphere. Quantification of hydrogen uptake/release is performed indirectly from hydrogen pressure changes in known volumes (Sievert method). The temperature range is similar to the gravimetric device, whereas the upper pressure limit is ~100 bar allowing the study of hydrogenation of complex hydrides.

5 Research examples

In the following section we have provided a couple of examples of recent efforts to integrate our experimental and theoretical work.

5.1 Magnesium based hydrides

The hydrogen absorption/desorption properties of magnesium has been the subject of intense research in the department during the eighties and early nineties. Furthermore, our recent theoretical work showed H₂ dissociation to be rate-limiting for hydrogenation on Mg(0001), and calculations of the electronic trends in hydrides of bulk Mg-3d transition metal alloys yielded little hope for a combined catalytic effect and significantly lowered hydrogen desorption temperature in such systems.

We recently took up investigations of dehydrogenation of magnesium based hydrides, emphasizing on the influence of air exposure, by means of time resolved in situ XRPD. By recording series of diffraction patterns with a time resolution down to 1-3 min it was possible to extract both structural and kinetic information.

Figure 6 Time resolved in situ XRPD study of the hydrogenation of MgH₂+Al at 400°C. Acquisition time per powder pattern is 150 s.

Figure 6 shows an in situ XRPD study of the dehydrogenation of a hydrogenated Mg₁₇Al₁₂ alloy. As seen from the figure, the Mg-Al alloy disproportionates into MgH₂ and Al during hydrogenation (t=0), and during dehydrogenation (t=2000-5000) the disproportionation is found to be reversible. Since no Mg is observed during dehydrogenation our results suggest that i) the Mg-Al alloy nucleates and grows from the (Al,Mg) fcc solid solution and ii) diffusion of magnesium in Al is fast compared to the
dehydrogenation of MgH2.

An analysis of the kinetics as a function of surface contamination with oxygen\(^{34}\) has revealed that the apparent activation energy for well activated samples of Mg-based hydrides usually lies in the range 100-170 kJ/mol, whereas exposure of Mg to oxygen leads to a drastic increase in apparent activation energy to approx. 300 kJ/mol.\(^{32}\) Kinetic results from time resolved in situ XRPD shows the apparent activation energy for Mg-Al and Mg-Cu alloys to be with 100-160 even after air exposure.\(^{31,33}\) This strongly suggests improved oxidation resistance due to the presence of alloying elements, possibly due to the creation of an amorphous oxide layer or a surface partially free of oxide.

In collaboration with the ICAT center at DTU, we have also investigated the growth and hydrogenation of magnesium thin films on a molybdenum substrate using a combination of XPS and DFT calculations.\(^{35}\)

### 5.2 Complex hydrides

As illustrated in the previous sections, we have worked intensively on NaAlH\(_4\), and our theoretical results on the nano particles are currently in the process of being investigated experimentally using microscopy and SAXS. In order to investigate the diffusion of hydrogen in un-doped NaAlH\(_4\) we have also carried out a combinatorial study involving DFT calculations and QENS experiments (Figure 5). The QENS experiments were performed at 60 K and 423 K, and we found the H-atoms jump with a frequency of approx. 10\(^{11}\) Hz, independent of the applied scattering vector (Q); probably due to either localized motion, high hydrogen content or maybe even multiple scattering. The ratio of the amplitude of the QE-peak to the amplitude of the elastic peak reveals that at 150°C only ~10% of the H-atoms in un-doped NaAlH\(_4\) are mobile. DFT calculations show that hydrogen can migrate from a AlH\(_4\) tetrahedron to a vacancy in a neighboring “tetrahedron” with a jump length of 2.6 Å and an activation barrier of 0.27 eV, but the vacancy formation energy is high, >1.5 eV.\(^{36}\)

In addition to NaAlH\(_4\) we have also investigated LiAlH\(_4\) using ball milling, differential scanning calorimetry (DSC), isothermal gravimetry, and XRPD.\(^{37}\) Figure 7 shows dehydrogenation curves of LiAlH\(_4\) ball milled for different periods of time.

*Figure 7 Dehydrogenation kinetics of LiAlH\(_4\) as a function ball milling.*

As seen in the figure, the dehydrogenation kinetics is enhanced significantly due to the mechanical treatment. A general trend of longer ball milling times leading to smaller crystallite sizes is found (as determined from XRPD line broadening), and ultimately faster kinetics for the transformation of LiAlH\(_4\) into Li\(_3\)AlH\(_6\). Interestingly, the transformation of Li\(_3\)AlH\(_6\) into LiH seems to be more insensitive towards crystallite/particle size reductions.
The effect of Ti-doping on the dehydrogenation behavior of LiAlH₄ is illustrated by the DSC traces (Figure 8) for as-received and TiCl₃·1/3AlCl₃ (2 mol %) doped samples. For the as-received sample, dehydrogenation proceeds through melted LiAlH₄ (1), which subsequently transforms into Li₃AlH₆ (2a) and finally into LiH (3), i.e. a three step mechanism.

The doping procedure results in a drastic reduction in the temperature for both the LiAlH₄ → Li₃AlH₆ transition (2b) and Li₃AlH₆ → LiH (3), thereby bypassing the melting of LiAlH₄, i.e. a two step mechanism.

Structural parameters and hydrogen positions in LiAlH₄ were obtained from DFT calculations, and further theoretical studies are focused on the potential effect of introducing alloying components.

6 Perspectives
Implementing rational design strategies based on a combination of state-of-the-art in theoretical methods with experiments covering synchrotron radiation and neutron sources are expected to accelerate the development of novel materials for energy storage. With particular focus on the nano scale properties of these materials and their catalysts, quantum leaps can be made in the understanding of the fundamental processes, and a continuous feed-back-loop between theoretical and experimental findings ensures a fast optimization scheme.

As described in this paper, the synergy is particularly high for the complex hydrides, which are dominated by light elements; although difficult to characterize experimentally, they often are easier to treat theoretically. The ability to perform reliable structural predictions of new stable hydride phases at finite temperatures and to calculate alloy compositions with specific thermodynamic properties can shorten the time scale for synthesis dramatically, thereby substantially increasing the possibility of finding viable alternatives to gasoline for the transport sector using a rational design approach.

Acknowledgements
The Danish Technical Research Council is acknowledged for funding the center of excellence Toward the hydrogen based society and the Danish Center for Scientific Computing (DCSC) for grants no. HDW-1101-05 and CPU-1104-15. The authors would like to thank Kim Lefmann, Jari i Hjøllum (both MRD, Risø), Dennis Engberg (Chalmers) and Christoph Niedermayer (PSI) for their assistance during the QENS
experiments. We are grateful to Jørgen Bilde-Sørensen (MRD, Risø) for his assistance with electron microscopy. Alfons M. Molenbroek and Robin Christensen (both Haldor Topøe A/S) are kindly acknowledged for providing essential equipment and technical assistance in relation to the time resolved in situ XRPD studies. Torben R. Jensen, Bitten Møller, Ronni Burkarl, Morten B. Sørensen (all from Aarhus University), Martin M. Nielsen (POL, Risø), Ove Rasmussen (MRD, Risø) and in particular Jens Wenzel Andreasen (POL, Risø) are sincerely thanked for their assistance with the in situ XRPD studies. Technical assistance from Mike Wichmann (MRD, Risø) during the building of the Sievert device is greatly acknowledged.

References

2 http://www.thecarconnection.com/index.asp?n=200&sid=200&article=7347
3 http://www.eere.energy.gov/hydrogenandfuelcells/posture_plan04.html
11 Dacapo pseudopotential code. URL http://www.fysik.dtu.dk/campos
19 T. Vegge, et al. (to be submitted).
33 A. Andreasen, T. Vegge, M. B. Sørensen, R. Burkarl, B. Møller, A. M. Molenbroek, A. S. Pedersen, T. R. Jensen, Dehydrogenation kinetics of air exposed MgH₂/Mg₃Cu and MgH₂/Mg₃Cu₂ studied with in situ X-ray diffraction, Appl. Phys. A. To be submitted (2005)
36 W. Stier, T. Vegge, and H. Jónsson (to be submitted).
37 A. Andreasen, T. Vegge, A. S. Pedersen, Dehydrogenation kinetics of as-received and ball milled Li₄AlH₁₀, In preparation (2005)
1. Introduction

Safety has always been a critical issue for innovations as it influences the economic attractiveness and public acceptance of any new idea or product. Furthermore, a fair market for trading innovative products has to be based on homogenized legal regulations, which usually refer to commonly accepted standards. Ideally, the development of these standards should be driven by industries and should be assisted by a consensus on safety assessments, based on profound and concerted research work.

However, in Europe the research related to hydrogen safety has been largely fragmented. This was the reason for the European Commission to support the needed integration and focusing of the related efforts with the help of a new instrument, the so-called Networks of Excellence NoE. So, the goal of the NoE HySafe is to provide the basis to facilitate the safe introduction of hydrogen as an energy carrier, by removing the described safety related obstacles. The integration of the dispersed efforts will thus contribute to a sustainable development in Europe. The objectives of the network are to

- strengthen, focus and integrate the fragmented research on hydrogen safety
- form a self-sustained competitive scientific and industrial community
- promote public awareness and trust in hydrogen technologies and
- develop an excellent safety culture.

The network has been constituted with 24 partners from 12 European countries and one partner from Canada, the University of Calgary. There are 12 partners from public research institutions, 7 industrial partners and 5 universities. More than 110 scientists from these institutions have been nominated to contribute to the network. This number was the basis for the determination of the maximum EC grant, which is 7 Mio Euro for 5 years. The total budget is 13 Mio for the same period.
The formal start of the network has been March 1st, 2004. In the meanwhile the organizational structure described below has been set up and all workpackages started their activities.

<table>
<thead>
<tr>
<th>Name of Institution</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forschungszentrum Karlsruhe GmbH</td>
<td>DE</td>
</tr>
<tr>
<td>L’Air Liquide</td>
<td>FR</td>
</tr>
<tr>
<td>Federal Institute for Materials Research and Testing</td>
<td>DE</td>
</tr>
<tr>
<td>BMW Forschung und Technik GmbH</td>
<td>DE</td>
</tr>
<tr>
<td>Building Research Establishment Ltd</td>
<td>UK</td>
</tr>
<tr>
<td>Commissariat à l’Energie Atomique</td>
<td>FR</td>
</tr>
<tr>
<td>Det Norske Veritas AS</td>
<td>NO</td>
</tr>
<tr>
<td>Fraunhofer-Gesellschaft ICT</td>
<td>DE</td>
</tr>
<tr>
<td>Forschungszentrum Jülich GmbH</td>
<td>DE</td>
</tr>
<tr>
<td>GexCon AS</td>
<td>NO</td>
</tr>
<tr>
<td>The United Kingdom’s Health and Safety Laboratory</td>
<td>UK</td>
</tr>
<tr>
<td>Foundation INASMET</td>
<td>ES</td>
</tr>
<tr>
<td>Inst. Nat. de l’Environnement industriel et des RISques</td>
<td>FR</td>
</tr>
<tr>
<td>Instituto Superior Technico</td>
<td>PT</td>
</tr>
<tr>
<td>European Commission - JRC - Institute for Energy</td>
<td>NL</td>
</tr>
<tr>
<td>National Center for Scientific Research Demokritos</td>
<td>EL</td>
</tr>
<tr>
<td>Norsk Hydro ASA</td>
<td>NO</td>
</tr>
<tr>
<td>Risø National Laboratory</td>
<td>DK</td>
</tr>
<tr>
<td>TNO</td>
<td>NL</td>
</tr>
<tr>
<td>University of Calgary</td>
<td>CA</td>
</tr>
<tr>
<td>University of Pisa</td>
<td>IT</td>
</tr>
<tr>
<td>Universidad Politécnica de Madrid</td>
<td>ES</td>
</tr>
<tr>
<td>University of Ulster</td>
<td>UK</td>
</tr>
<tr>
<td>VOLVO Technology Corporation</td>
<td>SE</td>
</tr>
<tr>
<td>Warsaw University of Technology</td>
<td>PL</td>
</tr>
</tbody>
</table>

Table 1: HySafe consortium members with their national origin

2. Networking
The basic organizational structure of the network consists of the Coordination Committee CC, the Network Governing Board NGB, the Advisory Council AC and the Project Management Office.

The NGB is the decision taking assembly consisting of one representative per consortium partner. It usually meets once a year.

The CC is composed of the workpackage leaders, the coordinator - who is the representative of the coordinating institution Forschungszentrum Karlsruhe in the case of HySafe - and representatives, mainly the coordinators, of the other relevant hydrogen related projects in the 6th Framework Programme, namely StorHy for the H2 vehicle storage, HYWAYS for general road mapping and NATURALHY for the usage of existing pipeline structures. The CC meets four times a year to report the progress, to develop recommendations for the NGB and thus by fact it steers the network.

The coordinator is the single point of contact of the network with the EC. Supported by the PMO he has to provide the daily management of the network including document management, information exchange. Presently the PMO consists of one secretary and the office leader.

The Advisory Council is an elected set of 12 experts which advises the NGB in all essential affairs. As there are AC members from Northern America and from Japan some links to the worldwide H2 hot spots outside Europe are established.

Of course not only the AC members provide some external links but also the strong involvement of many HySafe members in international groups. Many take an active role in the European and international standardization bodies CEN and ISO, few are even contribution to global regulations related to street vehicles GTR. The general communication with the EC and other industrial partners takes place in the Hydrogen and Fuel Cell Technology Platform HFP. Currently HySafe is applying to become a IPHE compliant project what offers to expose the networks activity on a international level.

These external relationship patterns are shown in Fig. 1.
3. Work Structuring

The structuring of the HySafe work follows a matrix arrangement with risk control levels from release, via ignition and fires, via explosions to mitigation and risk assessment control indicating the different columns. The rows are reserved for the different applications, like large scale production, distribution, street vehicles, other vehicles and portable applications. The expertise for the columns is manifested in the workpackages WP8 to WP12. The other workpackage have basic support character or are organizing dissemination activities. All 17 workpackages contribute to the network integration.

<table>
<thead>
<tr>
<th>WP</th>
<th>Name of Workpackage</th>
<th>Abbr.</th>
<th>Lead.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biennial Report on Hydrogen Safety</td>
<td>BRHS</td>
<td>INERIS</td>
</tr>
<tr>
<td>2</td>
<td>Integration of Experimental Facilities</td>
<td>IEF</td>
<td>FZJ</td>
</tr>
<tr>
<td>3</td>
<td>Standard Benchmarking Exercise Problems</td>
<td>SBEP</td>
<td>UPM</td>
</tr>
<tr>
<td>4</td>
<td>Scenario and Phenomenon Ranking</td>
<td>SPR</td>
<td>CEA</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen Incidence and Accident Database</td>
<td>HIAD</td>
<td>DNV</td>
</tr>
<tr>
<td>6</td>
<td>Principal CFD Exercises and Guidelines</td>
<td>CFDC</td>
<td>FZK</td>
</tr>
<tr>
<td>7</td>
<td>Mapping and Prioritisation Activities</td>
<td>MPA</td>
<td>Risø</td>
</tr>
<tr>
<td>8</td>
<td>Release, mixing and distribution</td>
<td>NCSRD</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Hydrogen ignition and jet fires</td>
<td>HSE/HSL</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Hydrogen explosions</td>
<td></td>
<td>FZK</td>
</tr>
<tr>
<td>11</td>
<td>Mitigation</td>
<td></td>
<td>GexCon</td>
</tr>
</tbody>
</table>
Table 2: Workpackages

The obvious clustering of the workpackages will help to simplify the relative complex structure of HySafe in the near future.

4. First Integration Success
A detailed catalog of the experimental facilities has been compiled. It contains more the 80 hydrogen specific testing facilities including all relevant details. It has been published on the HySafe website http://www.hysafe.org/index.php?ID=40&deliverable=9.

WP4 organised a Phenomenon Identification and Ranking Table PIRT. PIRT analyses are well established in nuclear research and are based on experts’ judgments. For this activity a very detailed table differing and labeling all different phenomena has had to be developed. The major outcome of the first voting is that small releases in confined or partially confined areas especially from small electrolyser and large scale transportation through tunnels play the most important role and should be treated first.

These results supported by an ad-hoc “Macro-PIRT” helped to define the first set of headlines namely “(Partially) Confined Releases” and the related “Mitigation” measures. The headline concept has been established to orientate the network on intermediate time scale (proposals for experiments, benchmarking,…) internally, but also to indicate “what’s going on in HySafe” to the externals.

For the database of WP5 the input template and the data record definition have been agreed.

In WP6 the initial set of benchmarking examples has been determined in cooperation with WP7. The results of the first two obligatory benchmarking examples SBEPV1 and SBEPV2 have been delivered by all participating consortium members. Both have been open benchmarks, in SBEPV1 there is a release in a large cylindrical vessel initially filled with air and with a diffusion controlled long phase after the release, SBEPV2 provides the transient combustions of a large hemisphere filled with stoichiometric hydrogen air mixture and covered only with a foil. Despite the simplicity of both experiments the experimental simulations deviate considerably.
WP7 conducted a state-of-the-art survey where all projects the partners are involved in currently are listed and organized and on-line questionnaire where besides all HySafe experts also externals have been asked to give their view on the present gaps and research necessities. All this work had considerable impact on the definition of the second year program and on the formulation of the headlines mentioned above.

The website www.hysafe.org has been set up earlier than planned (see Fig. 2). It consists of a public and an internal part. All members have the ability to edit the pages in a controlled way. The network documents, as there are deliverables, meeting minutes, decision and presentation proposals as well as (external) background information may be up- and downloaded to and from the webpage. Additionally some anonymous email addresses like coordinator@hysafe.org and complete email lists like group.WP16@hysafe.org have been set up.

The newsgroups services have been set up. However, due to the need for special newsgroup reader software the acceptance of this alternative communication channel has not been accepted broadly so far.

The website provides a feature which allows for an online organization of the different meetings. A database for all personal data which may be exhibited deliberately is included. Again every member has full control, especially on his data and data presentation.

The website integrates the online presentation of the experimental facilities, support the online editing of the BRHS and of the curriculum of the e-Academy. It will provide an interface to the HIAD database.

So, effectively the website is the communication platform and pools and supports all the workpackages at one reference location.
5. Projects

As the integration objective cannot be effectively provided only on an abstract level, working together in the conventional way, namely on a project manner, is the essential means to reach it. Mainly two different sorts of projects have been identified as important constructions for HySafe.

Internal projects are set up by defining an ideal project goal following the current headlines. With this ideal concept one tries to identify which efforts, currently going on or presently planned at each partner institution, could fit into this framework. Then it should be tried, if necessary, to redirect parts of these activities to fill gaps with respect to the project objectives or to remove double work. This will transform the fragments to an integrated procedure with an higher overall efficiency and potentially broadly accepted outcome.

External projects are mainly driven by third parties financing the major work of a project but still with more than one HySafe partner involved.

All HySafe projects are characterized by covering several workpackages by their topics and including several HySafe partners. Furthermore, all projects have to provide the classical clear time planning, resources allocation and project objectives.

Other relevant activities can be mostly attributed to one of the existing workpackages.
For the new yearly planning of 2005/2006 two internal projects have been decided which definitely account for the current headlines “(Partially) confined releases” and related “Mitigation”.

**InsHyDe**

In a medium term future, one could expect an increasing number of hydrogen systems to be used (co-generation processes) or stored (mobile applications) inside buildings (dwellings, garages,…). Whereas outside location would be favourable in most cases to prevent leaking hydrogen from accumulating, inside location will remain in many cases a necessity.

On this issue, the PIRT exercise (WP4) and the survey (WP7) have pointed out that releases (even slow releases, with “small” release rates) of hydrogen in confined or semi-confined geometries present a serious risk, since combustible mixtures may form, which, if ignited, could lead to explosions.

However, it seems that no recommendation exists today to provide advice on the safe use of hydrogen systems in confined spaces. Many questions remain unanswered and especially those related to hydrogen dispersion behaviour depending on the leaking regime. Effect of safety measure such as ventilation is also insufficiently understood although it is a fundamental and widely used risk control technique.

This program intends to investigate realistic (ATEX related) indoor leaks and ultimately to provide recommendations for the safe use / storage of indoor hydrogen systems.

This program also aims at pulling together workpackage proposals and existing research projects toward a common goal and a useful contribution to the society for the safe implementation of hydrogen technologies.

The objectives may be summarized to

- provide information on main hazards when using hydrogen in confined spaces (hydrogen dispersion behaviour, fire and explosion potentials, ignition),
- provide information on the regulatory and standards framework for the use of hydrogen systems inside buildings (ATEX directives and related standards, fire safety rules,…),
- help end users and designers to assess potential leaking rates (risk assessment) and regimes of planned and existing indoor hydrogen systems,
- give advice on ventilation performance (reliability, flow, layout,…) to ensure that leaking incidents do not allow hydrogen to accumulate,
- give advice on sensors layout and performances based on expected releases and buildings layout
- give advice on recombiner layout and performances based on expected releases and buildings layout,
- give advice on choice of electrical equipment inside the building,
• give advice on building layouts (inclined ceiling, choice of electrical equipment, room size, fire safety,…),
• and eventually, give advice on best practices modelling of indoor release of hydrogen,
• validate existing permeation rates proposed in draft automotive legal requirements and standards particularly for buses/commercial vehicles
• propose alternative permeation rates for automotive legal requirements and standards if the existing proposals are found to be excessively conservative.

HyTunnel
The Phenomena Introduction and Ranking Table (PIRT) exercise has highlighted that hydrogen powered vehicles in the confined space of a tunnel could pose a serious hazard of fire and explosion to the tunnel and its users. The PIRT exercise has also identified a number of scenarios associated with the use of such vehicles in a tunnel. It is therefore crucial that to ensure the safe introduction of hydrogen-powered vehicles into the tunnel traffic, these scenarios are properly understood and their hazard and risk assessment carried out in relation to the conventional fuel powered vehicles. The distribution and mixing characteristics of a new fuel of hydrogen, and any potential development of fire and explosion under normal and emergency mode of operation of the tunnel ventilation need to be understood. The appropriate risk assessment strategies and adaptation of safety concepts of existing tunnels will then have to be devised. For future constructions, design characteristics need to be determined, aiming at a synchronous advance of vehicle and infrastructure technology. Where possible, the study is intended to address various mitigating design measures, hydrogen flow rates, combustion speeds, pressure loads, and ignition times and locations.

A systematic approach to achieving the goal of the safe introduction of hydrogen powered vehicles in tunnel starts with a state of the art survey of tunnel safety technology. Current regulations and standards, fire and explosion mitigation techniques in present day and planned tunnels need to be investigated. Certain worst-case scenarios of hydrogen-powered vehicle or fuel supply truck accidents, as identified through PIRT exercise, shall be selected and examined by using CFD-simulation (and could form part of next SBEP exercise) and verification experiments building on the work of earlier projects such as EIHP. Relative hazard and risk assessment of conventional petrol/diesel run vehicles with CG2/LH2 powered vehicles (including cars and commercial vehicles) will be undertaken. Finally guidelines for vehicle and tunnel safety systems shall be developed countering hazards associated with the release of hydrogen in a tunnel, which will be forwarded for consideration by bodies such as UNECE WP29 for vehicles.

The technical objectives are
• Review current regulations and standards, fire and explosion mitigation techniques in present day and planned tunnels dealing with conventional
fuel (petrol/diesel) vehicles; Assess them with standards and guidelines produced under other EC funded projects (HYAPPROVAL, HYCOM, HYGUIDE,…).

- Review scenarios of hydrogen-powered vehicle or fuel supply truck accidents. (The PIRT exercise is only of value as a “rough cut” tool, the actual scenarios need to be identified in a structured manner by experts in the appropriate systems)
- Understand distribution and mixing characteristics of a new fuel of hydrogen, and any potential development of fire and explosion under normal and emergency mode of operation of the tunnel ventilation (longitudinal, transverse, semi-transverse, etc.) system, with and without existing or future mitigation measures. In particular any release or tunnel characteristics that can lead to high speed deflagrations or DDT need to be identified.
- Undertake CFD simulations & verification experiments for providing relative risk assessment of conventional fuel vehicles with CG2/LH2 powered vehicles (including cars and commercial vehicles)
- Develop guidelines for tunnel and vehicle safety systems countering hazards associated with the release of hydrogen in a tunnel.
- Develop a road map for the introduction of the guidelines to the appropriate forums for introduction to appropriate legal requirements, etc.

The further work program is orientated not only at the results of a state-of-the-art report and a PIRT analysis performed within the NoE but also complies with the needs identified in the external network including other European projects related to hydrogen like StorHy, HyWays, NATURALHY and the steering H2/FC technology platform of the EC. The coordination with activities outside Europe could provide further opportunities to all parties involved, not only by avoiding redundant work.

6. Dissemination


Educational programs are being designed. They will be the first educational programs of this kind and quality in Europe. The current version of the curriculum designed for safety engineers may be browsed on http://www.hysafe.org/index.php?ID=68.

A summer school will be set up already this year, provided some additional financial support from the EC will be granted in the frame of the Marie-Curie-Program.

To open up the network a supporters group has been recently established. Supporters must be registered and will get access to a specific section of the HySafe website, the Supporter Section (internal login via...
www.hysafe.org/login.php). The state of HySafe Supporter will be granted by the HySafe consortium. A Supporter can be any organisation working in the same field as HySafe or in related fields of hydrogen safety including research, equipment, product development, safety assessments, education, regulations, codes and standards. The origin of the Supporter is not limited to European Union countries.

The first International Conference on Hydrogen Safety will be organized in 2005. It is the first Conference dedicated to the hydrogen safety topic. It will host the first workshop of the IPHE RC&S workshop. The conference is organized in cooperation with the Japanese project ArdentHy, the EC projects StorHy, NATURALHY and CUTE, the International Association for Hydrogen Energy and the Italian National Firecorps. It will take place in September 8-10, 2005 at the Congress Palace, Pisa, Italy. The sessions will chaired pair wise by industry and research specialists. For further information se the HySafe website or go directly to http://conference.ing.unipi.it/ichs (see Fig. 3)

Figure 3: Entry of the ICHS webpage

7. Conclusion and Outlook

The NoE HySafe has started properly and the first jointly performed research projects are on the way. This proves that integration has been initiated and eventually will be furthered by this “real” work – at least within the HySafe consortium. Of course external integration, i.e. international collaboration, will be an essential criterion for
establishing any hydrogen economy, as also the negative information on accidents won’t stop at borders.
Not only, but especially support for RC&S and educational efforts have to be considered as long lasting efforts. This is why knowledge generated and usually linked to individuals has to be saved even after the period of financial support. So, suitable concepts for maintaining such networks have to be developed within the next few years.
However, by shifting work to at least partially privately financed safety related work, the NoE HySafe will prove that it will be well positioned in the future market of hydrogen safety services.

Acknowledgement

The research project NoE HySafe is supported by the European Commission under the 6th Framework Programme and contributing to the implementation of the Key Action "Integrating and strengthening the ERA" within the Energy, Environment and Sustainable Development (Contract n°: SES6-CT-2004-502630). In behalf of the whole consortium the author of this article would like to thank the EC for this grant.
Session 5 – Fuels and Technologies for the Transport Sector

Chairman: Jürgen Schmid, ISET, Germany
The Benefit of integrated Energy and Transportation CO₂ Emission Control Strategies

Ebbe Münster, PlanEnergi s/I, 9520 Skørping, Denmark
TEL: +45 96 82 04 00, E-mail: Em@planenergi.dk

Henrik Lund, Department of Development and Planning, Aalborg University, Denmark
TEL: +45 96 35 83 09, FAX: +45 98 15 37 88, E-mail: Lund@plan.aau.dk

Abstract.
This paper analyses mutual benefits of integrating future energy and transport CO₂ emissions control strategies. The paper illustrates and quantifies for the case of Denmark the mutual benefit of integrating the transport and the energy sector. In short, the energy sector can help the transport sector in replacing oil by renewable energy and CHP. While the transport sector can help the energy system in integrating a higher degree of intermittent energy and CHP.

Two scenarios for partial conversion of the transport fleet have been considered. One is battery cars combined with hydrogen fuel cell cars and the other is the use of biofuel (ethanol) and synthetic fuel (methanol) for internal combustion cars. Both scenarios have a substantial effect on decreasing the excess electricity production caused by an eventual increase in the fraction of electricity delivered by fluctuating sources like wind turbines.

1 Introduction
Most governments distinguish between the transport and the energy sector, when making strategies for the implementation of CO₂ emission controls. In the energy sector, measures, such as energy conservation and renewable energy are very often proposed, while in the transport sector most countries experience a steady growth in oil consumption without being able to implement measures to stop the growth. This paper analyses mutual benefits of integrating future energy and transport CO₂ emissions control strategies.

When the Danish Parliament in 1990 formed the first objectives of CO₂ emission controls, the target was formulated as a 20 percent cut in year 2005 compared with year 1988. Additional targets have been added for year 2030 and the Kyoto Protocol Period (2008-2012). In the implementation strategies, the energy sector is expected to provide for most of the cut in CO₂ emissions. Moreover, the targets for the transport sector have been adjusted several times, because Denmark has failed to implement suitable policies.

Therefore the energy and the transport sectors are facing two very different challenges today. The transport sector is in a situation where oil consumption should be decreased, and the sector has no known measures or strategies for doing so. One perspective would be to introduce electric vehicles and hydrogen vehicles or to replace petrol by ethanol and methanol. On the other hand the energy sector in Denmark has implemented wind
power and CHP (Combined Heat and Power production) to a degree which is now causing an integration problem. Time differences between demand and supply simply forces the system to make excess electricity productions.

Fig. 1.1 illustrates the problem. It shows the electricity balance for West Denmark (Jutland and Funen) for a typical 24 hour period. It is seen how excess electricity production occurs because the wind turbines produce according to the wind, the CHP’s produce according to the heat demand and the power plants must keep a certain minimum fraction of the production for stability and regulation purposes.

The purpose of this paper is to illustrate and quantify the mutual benefit of integrating the sectors for transport and energy. In short, the energy sector can help the transport sector replace oil with renewable energy and CHP. The transport sector, on the other hand, can help the energy system by integrating a higher degree of fluctuating renewable energy and CHP.

2 Energy system analysis methodology

The large-scale integration of wind power has been analysed by modelling the western Danish collective energy system (electricity and district heating) in year 2020 on the EnergyPLAN computer model including the implementation of the Nord Pool market. The EnergyPLAN model is a deterministic input/output simulation model. General inputs are demands, capacities and the choice of a number of different regulation strategies, emphasising import/export and excess electricity production. Outputs are energy balances and resulting annual production, fuel consumption and import/export. For a detailed description of the model, please consult (Lund, Münster and Tambjerg, 2004; Lund and Münster, 2003).

The energy system in the EnergyPLAN model includes heat production from solar thermal, industrial CHP, CHP units, heat pumps and heat storage and boilers. District heating supply is divided into three groups of boiler systems and decentralised and
centralised CHP systems. Additional to the CHP units the systems include electricity production from renewable energy, i.e. photovoltaic and wind power input divided into onshore and offshore, as well as traditional power plants (condensation plants).

**Fig. 2.1. EnergyPLAN system model.**

The model is simple in the respect that it aggregates all units in each of the mentioned types in the modelled region into one unit with average properties. This means that the differences among the single units and the transmission among them are not considered. On the other hand it is advanced in the respect that it uses detailed hourly distributions of heat demands, electricity demands, wind production etc. to analyse the behaviour of the entire system hour by hour for a whole year. Various constraints, operational strategies and changes to the system can be imposed and compared.

The inaccuracy caused by the aggregation has been evaluated by testing the effect of replacing the single CHP-unit with ten different interconnected units each with properties related to actual Danish plants with differences in size, amount of heat storage etc. The difference between these two situations was found to correspond to changes in the specifications for the CHP-unit of app. 3%, and such difference are now being compensated in the EnergyPLAN model.

The model requires four sets of input for the technical analysis. The first set is the annual district heating consumption, and the annual consumption of electricity, including flexible demand and electricity consumption from the transport sector, if any. The second set is the capacity of photovoltaic and wind power, including a moderation factor, in order to adjust the relationship between the wind capacity and the correlating electricity production. This part also defines solar thermal, industrial CHP heat production inputs to district heating. The third set is capacities and operation efficiencies of CHP units, power stations, boilers and heat pumps. And the last set specifies some technical limitations; namely the minimum CHP and power plant percentage of the load in order to retain grid stability. Furthermore, it includes the maximum heat pump percentage of the heat production, in order to achieve the specified efficiency of the heat pumps.
For the economic calculations of exporting and/or importing electricity, the model needs input to define price variations on the international electricity market. The model has an internal hour by hour standard price variation based on historical data from the Nord Pool market. These price variations can be adjusted by the following inputs: A multiplication factor, an addition factor (€/MWh) and an adjustment price of non-predictable export/import. Moreover, a factor expressing market reactions to wind and CHP can change the market. Such factors have been used to implement the model of Nord Pool as described in (Lund and Münster, 2004). The price elasticity factor used is 3 €/MWh/GW. The price level at the Nord Pool spot market and the function of the bottlenecks at the international transmission lines are heavily influenced by the water level of the Norwegian and Swedish hydro power reservoirs. In the following all economic calculations are made as averages on a 7-year period consisting of one dry year, three normal years and three wet years. (Norsk Olie- og energidepartement, 2001)

Furthermore, input is needed in terms of marginal production fuel costs. In accordance with the expectation of the Danish Energy Agency (Danish Energy Agency, 2003) the following prices for 2020 have been used in the reference calculation: 1.8 €/GJ coal, 4.0 €/GJ oil, 3.7 €/GJ Natural gas and 3,2 €/GJ for biomass (straw).

The model emphasises the consequences of different regulation strategies. Basically, the technical analyses distinguish between the two following strategies:

Regulation Strategy I: Meeting Heat Demand: In this strategy all units produce solely according to the heat demands. In district heating systems without CHP the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are given priority according to the following sequence: Solar thermal, industrial CHP, CHP units, heat pumps and peak load boilers.

Regulation Strategy II: Meeting both Heat and Electricity Demands: When choosing strategy II, export of electricity is minimised mainly by replacing CHP heat production by boilers or by the use of heat pumps. This strategy increases electricity consumption and decreases electricity production simultaneously, as the CHP units must decrease their heat production. With the use of extra capacity at the CHP plants combined with heat storage capacity, the production at the condensation plants is minimised by replacing it with CHP production.

In the economic analysis the two strategies mentioned above are moderated by a market trade strategy based on the principle of exporting when the market prices are higher than the marginal production costs and importing when they are lower than the marginal production costs. In all strategies the model takes a number of restrictions and limitations into consideration, such as:

- the system needs a certain degree of grid-stabilising capacity
- bottlenecks in external transmission capacity
- strategies for avoiding critical surplus production
- maximum percentage of heat production from heat pump
2.1 Reference Energy System

The western part of Denmark in 2020 has been chosen as a reference scenario. The region is identical to the area of the transmission system operator Eltra. This reference scenario is based on the ELTRA system plan 2001 and was used in the work of an expert group, which in 2001, on request of the Danish Parliament, investigated the problem of large-scale integration of wind and analysed possible means and strategies for managing the problem (Danish Energy Agency, 2001). As part of the work, Aalborg University made some long-term 2020 energy system analyses of investments in more flexible energy systems in Denmark (Lund and Münster, 2001).

The reference was constituted by the following development: the Danish electricity demand was expected to rise from 35.3 TWh in 2001 to 41.1 TWh in 2020 equal to an annual rise of approximately 0.8 per cent. The installed capacity of wind power in 2001 was expected to rise from 570 to 1850 MW in East Denmark and from 1870 to 3860 MW in West Denmark in 2020. The increase is primarily due to the implementation of one 150 MW offshore wind farm each year. Existing large coal-fired CHP steam turbines are replaced by new natural gas fired combined cycle CHP units when the life of the old CHP plants expires.

Reference- and Alternative Regulation Systems

The reference regulation system has been defined as the present regulation adjusted by a number of likely measures to avoid critical excess production. Thus the reference regulation can be described in the following way:

- All wind turbines produce according to the fluctuations in the wind
- All CHP plants produce according to the heat demand (or the triple tariff)
- Solely the large power stations participate in the task of balancing supply and demand and securing grid stability
- Minimum 300 MW and minimum 30 percent of the production must come from grid stabilising power stations
- Critical excess is avoided by using the following priorities: 1) replacing CHP with boilers, 2) using electric heating and 3), if necessary, stopping the wind turbines.

In (Lund et al 2004) the ability of the reference system to integrate wind power has been compared with a number of alternative flexible regulation systems based on the following principles:

- CHP-units operate in order to integrate wind power by reducing their electricity production in hours of excess production. Instead a boiler, and/or electric heating, and/or a heat pump replace the heat production.
- Small CHP-units are included in the grid stabilisation task.

The feasibility of such flexible energy systems has been evaluated on its ability to exploit the Nord Pool market. The following set of assumptions has been created to generate a likely reference development:
• marginal wind production costs of new offshore wind farms 29 €/MWh.
• international CO2 trade price in 2010-2020: 13 €/MWh

Especially one alternative proved to be very efficient and cost effective, namely the investment in heat pumps in combination with the above change in regulation of the CHP plants. In the following, the heat pump alternative have been combined with two transport system scenarios.

2.2 Transport system scenarios

In order to investigate the influence on the existing electrical system of an eventual electrification of part of the transport system two scenarios for this has been established for the year 2020.

One is based on a research project carried out by Risø National Laboratory with the title: ‘Electric Vehicles and Renewable Energy in the Transport Sector – Energy System Consequences’, which was documented in 2000. (Nielsen and Jørgensen, 2000).

This report concludes that the technical performance – in particular the range – of battery cars and hydrogen fuel cell cars will gradually improve in the coming decades, making it feasible for this type of cars to take over a substantial part of the transport work, particularly for passenger cars and small delivery vans below 2 ton.

Fuel cell cars operating on synthetic fuels like methanol are left out because of a poorer overall efficiency.

The used scenario shown in the figure below is scaled down to fit to West Denmark only and assumes a 27 % substitution of passenger cars and small vans by battery cars combined with a 14 % substitution by hydrogen operated fuel cell cars in 2020.

![Transport scenario # 1](image)

Fig. 2.2.1 Transport scenario # 1.

The batteries of the cars are assumed to be big enough to level out consumption on a 24-hour basis (loading during the night), while the combined H2 storage of the electrolyser plants and the cars is considered capable of levelling out consumption on a 4 weeks basis. The electrolyser are dimensioned to operate app. 4000 hours per year.

The heat produced by the electrolyser is not considered in the model. If the electrolyser are placed close to CHP plants the produced heat could have a positive effect on the balance in the grid because the heat will occur in periods where the system needs to increase electricity consumption. If the produced heat is used by the district heating network is will cause a
lower heat – and hence electricity – production of the CHP plant. This effect can not be modelled by the present version (6.5) of the EnergyPLAN model, but is considered for the next version.

An alternative scenario based on liquid fuels (biofuels and synthetic fuels) used by internal combustion engine cars is presented in fig. 2.2.2.

**Fig. 2.2.2 Transport scenario # 2.**

This scenario is based on the RETrol-vision of the Danish power company ELSAM. (Elsam, 2005).

It has been scaled to provide the same petrol substitution as scenario # 1. It is seen that is has a lower overall efficiency, but it can not be directly compared to # 1 because it assumes the use of cars, which are either standard cars (low percentage mix of Et or Met with petrol) or slightly converted (higher percentages mix). Hence the total cost of the system including conversion of the fleet is much lower.

In this case the heat balance is negative (because the heat produced by the internal ignition engines of the cars is not considered). The consumed heat is provided as waste heat from condensing power plants.

An important asset of this scenario is that the ethanol fermenters produce the carbon needed for the production of methanol. In this way the total system including the cars can be regarded as CO₂ neutral.

Apart from ethanol the fermenter produces a solid biofuel. This fuel has been subtracted in the biomass input.

Like in # 1 the electricity consumption is assumed to be flexible to the extent that it can level out electricity consumption on a 4 weeks basis.

### 3 Results

#### 3.1 Electricity excess production

The first comparison depicted shows the ability to decrease electricity excess production caused by wind power by the various systems considered.
The ‘Ref’ curve of fig. 3.1.1 shows how most of the wind power electricity must be exported from West Denmark in 2020 if the reference regulation method described in section 2.1 is used. Note that 25 TWh of wind power correspond to 100% electricity demand of West Denmark.

If 350 MW-e of heat pumps are established at the CHP’s and the alternative regulation method is used the situation improves considerably.

If transport scenario # 1 (EV/HFCV) is introduced instead it has more or less the same effect.

Transport scenario # 2 (Et/Met) has a larger impact because it uses more electricity.

A combination of the heat pumps and scenario # 2 is only marginally better because the constraint of the minimum fraction of power plants for stabilising purposes puts a limit to the regulation possibilities.

If this constraint is eased by assuming that 50% of the wind turbines are supplied with advanced high-voltage semiconductor regulation equipment, making it possible for them to perform phase- and frequency regulation, the situation is again much improved. (Et/Met + HP + W). This type of equipment is available to-day and is considered economically feasible for the very big offshore turbines that will be established in the future. It is particularly relevant for the combination wind-turbine/electrolyser because this combination can perform both up- and down regulations when both parts are active.

3.2 Socio economy

In the former section it was seen how the electrification of part of the transport fleet could improve the ability of the energy systems to incorporate wind turbines.

In this section the involved socio economy will be discussed. It is noted that the costs of the conversion of the transport system itself are not considered. We restrict ourselves to looking at the economic consequences of such conversions on the rest of the energy system.
Fig. 3.2.1. *Net trade income in West Denmark, 2020.*

Fig. 3.2.1. Illustrates the ability of the different systems to trade on the Nord Pool market. The figures in the graph are relative to a situation with no wind power and no trading. In the reference situation wind power above 6-7 TWh/year starts to decrease and above 15 TWh/year even causes the net result for West Denmark to become negative because the marginal value of each MWh produced cannot finance the cost of establishing and operating the wind turbine.

Adding 350 MW of heat pumps improves this situation considerably. The costs of this investment are included.

Combining the heat pumps with the two transport scenarios further moves the optimum for the wind power to the right. The vertical position of the curves for the transport scenarios should not be emphasised since the cost of converting the cars and establishing the distribution systems are not included. The reason for the scenario #2 to have lower incomes than #1 is mainly that it involves the use of biomass the cost of which is included in the model.

This problem is avoided in the next figure, which shows the marginal benefits of adding extra wind power to the system.

Fig. 3.2.2. *Marginal costs and benefits for West Denmark, 2020.*
In this figure it is seen how the optimal amount of wind production increases when the flexibility of the system increases. (Note the different scaling from fig. 3.2.1.). Optimal wind production moves from about the present situation for the reference system to 40 and even to 50 % of the demand when heat pumps and transport electrification are assumed. Scenario # 2 has the highest optimum because it uses more electricity than # 1.

4 CO₂ emission

In this section the impacts of the various systems on the CO₂ emission of West Denmark in 2020 are calculated. The calculations extend to the total energy system including the part of the transport fleet involved in the two transport scenarios (app. 40% of the cars below 2 ton).

In this calculation no corrections are made due to export and import of electricity. As the export increases significantly with higher wind productions it can become relevant to make such corrections. Very complicated simulations of the entire electrical system of Northern Europe are needed to make such corrections accurately (e.g. by the Balmorel software) but it is possible to get a fairly good estimate of the result by using simple key figures for CO₂ emission for marginal MWh in our neighbour countries. In the figure below the following figures have been assumed:

- For normal and dry years: 0,5 t/MWh
- For wet years: 1 t/MWh (Lund et al, 2004)
ig. 3.3.2. Net CO₂ emission for West Denmark, 2020.

Not surprisingly this figure shows the benefits for the global CO₂ emission of adding wind turbines in Denmark. It also shows that it makes little difference for this emission whether we use electricity for cars in Denmark or export the electricity to be used for substitution of coal or gas somewhere else. It should, however, be noted that the flexibility adding measures discussed in the preceding sections are necessary to facilitate high wind power fractions. It should also be noted that the demand for ‘clean’ electricity by our neighbours lasts only until they convert their own systems.

5 Conclusion

In the calculations two scenarios for partial conversion of the transport fleet have been considered:

# 1: Battery cars combined with hydrogen fuel cell cars.

# 2: Use of biofuel (ethanol) and synthetic fuel (methanol) for internal combustion cars.

In both cases substitution of app. 40% of petrol consumption for cars below 2 ton is assumed in 2020.

Both scenarios have a substantial effect on decreasing the excess electricity production caused by an eventual increase in the fraction of electricity delivered by fluctuating sources like wind turbines. In a situation where 50% of the electricity production is fluctuating, both scenarios decrease the excess electricity production by app. 70%. The decrease is much bigger than the actual amount of electricity used for transport because of the ability of this particular demand to be placed at the critical hours.

The total economy of conversion of the fleet has not been calculated, but the positive effects on the economy of the rest of the energy system have been evaluated.

It is shown how the use of electricity for transport increases the optimal amount of wind turbines in West Denmark. While the establishment of 350 MW-e heat pumps at the cogeneration plants (CHP) increases this optimum from app. 25% to app. 40% in 2020, the additional electrification of the transport fleet further increases the optimum to app. 50%.

Calculations on CO₂ balances show that the two scenarios cause a saving of app. 1 Mt CO₂ for West Denmark. If the indirect CO₂ savings in the neighbouring countries caused
by export of electricity is considered, it is, however, shown that the above mentioned increase of the amount of wind turbines causes bigger savings (app. 2 Mt).

References

Danish Energy Agency (2001) Rapport fra arbejdsgruppen om kraftvarme- og VE-elektricitet (Report from the expertgroup on CHP- and RES-electricity), Copenhagen, Danish Energy Agency

Danish Energy Agency (2003) Brændselsprisforudsigelser


Norsk Olie- og energidepartment (2001) St.meld.nr.37: Om vaskrafta og kraftbalancen
FellowSHIP - Fuel Cells for Low Emission Ships

A project presentation

Tomas Tronstad, Det Norske Veritas
Øyvind Endresen, Det Norske Veritas

DNV Research, Veritasveien 1, N-1322 Høvik, Norway. Tel. +47 6757 9496,
tomas.tronstad@dnv.com

Abstract:

Fuel cell technology holds promising results, but fail to meet the requirements of large industrial applications, such as for ships and offshore. The poor load-following performance of high temperature fuel cells is one short stopper. The goal of the FellowSHIP project is to develop, design, build, test and qualify integrated system solutions that will enable today’s fuel cell to meet industrial requirements. The power packs build on fuel cell technology in patented configurations with steam turbines, in combination with new electro- and automation system solutions. This paper presents findings mainly from the Fellowship project, and complemented with other related R&D projects. We focus on fuel cells for shipboard use; investigated for offshore supply vessel, ro-ro cargo vessel and passenger vessel. The use of hybrid Fuel Cells systems was compared to conventional gas/diesel engines for various fuel options. Our modeling clearly indicates significant reduced emission and fuel consumption by use of fuel cells. The principles of Life Cycle Assessment (LCA) were applied to study cradle-to-grave impacts. The results show that fuel cell technology offers 35-90% better environmental performance in the impact categories for global warming, photochemical oxidation and acidification compared to conventional auxiliary plants onboard passenger ships. The FellowSHIP project phase 1 has been successful with no immediate showstoppers identified.

Introduction

Ship transportation accounts for almost 2/3 of world global trade, and is generally considered environmental friendly compared with other transportation means. Nevertheless, ship emissions generated by the merchant fleet are reported to represent a significant contribution to the global anthropogenic emissions of NOx (~15%), SOx
while only about 2% of the CO₂ emissions /1/, /2/. The large NOx and SOx emissions is reflecting the poor fuel qualities and the high NOx producing machinery often used in ships. In order to reduce emissions, measures can be initiated before start of the combustion process (fuel oil treatment and fuel oil modifications) and during the combustion process (reduce formation of air pollutants in the combustion process). The fuel consumption and emissions may also be reduced by improved technical condition (hull shape, propeller, antifouling systems, engine efficiency), operational means (reduced speed, weather routing, more efficient use of available cargo space, reduced time in ballast), alternative fuels (e.g. LNG, hydrogen) and alternative propulsion systems (e.g. fuel cells, sails).

Fuel cells have become a subject of intense research during the last decade. This research is both driven by the expected performance and efficiency, and the political pressure to reduce emissions. For instance, US Environmental Protection Agency, the EU and the International Maritime Organisation will work for lower ship air emissions in the future. (/3/, /4/, /5/, /6/). Fuel cell concepts with highly efficient electric drive systems can provide energy efficient, zero emission propulsion concept for the future. Compared to conventional diesel engine or gas turbine technology, fuel cell systems also offer reductions in generated noise and vibration. Presently, fuel cell technology receives much attention as a possible mean to reduce atmospheric emissions from power producing machinery.

This paper presents some of the main findings from the joint industry project FellowSHIP phase 1 and environmental studies of fuel cell technologies in ships.

The **FellowSHIP** project

1.2 Project short description

The goal of the FellowSHIP project is to develop, design, build, test and qualify integrated system solutions that will enable today’s fuel cell to meet industrial requirements. The project started in 2003 and consists of the following 3 phases:

- **Phase 1**: Feasibility study, development of basic design. Completion June 2005.
- **Phase 2**: Within December 2007, develop, design, build, test and qualify the new 330kW MTU fuel cell power pack and the new 25-50kW Wärtsilä fuel cell.
- **Phase 3**: Develop, design, build, test and qualify the fuel cell + steam turbine in the new machinery configuration. Planned power sizes include megawatt arrangements.

The project focus is on system arrangement, integrating proven turbine technology with state-of-the-art fuel cell technology. The turbines provide safety redundancy to the less proven fuel cell technology, building confidence for owner, approval authorities and...
customers. The patented system configurations enable the fuel cells to run at steady state conditions. At the same time, the total power pack complies with severe dynamic operating requirements.

In 2003, Shipowner Eidesvik launched the world’s first LNG powered offshore supply ships. Wallenius are recognised as one of the most environmental focussed ship operators. The ship owners are planning to take the fuel cell technology onboard for demonstration and qualification. The project companies possess the competencies and ability needed to develop, integrate, qualify and build the total power pack technology. The project has teamed up with fuel cell suppliers MTU and Wärtsilä. Both suppliers are now developing maritime versions of their products, considering physical conditions and the operational requirements of such applications. The FellowSHIP project will demonstrate and test both technologies.

In their respective business areas, the partners main motives are to develop technological basis for future commercial solutions. Short term commercial lift-off in of fuel cell technology is anticipated to be confined by high capital cost. However, the longer term prospects are promising, including the implications of fuels such as hydrogen and natural gas. The technology lead gained through the FellowSHIP project will provide the partners a unique position in their respective business areas in addition to the marketing effect.

Some main innovative aspects of the project are:

- The first industrial fuel cell power pack developed for rough industry applications, especially suitable for marine and offshore use.
- The world’s first demonstration of large scale fuel cells onboard merchant vessels.

The main partners of the project are Aker Kvaerner Power and Automation Systems (Norway), Det Norske Veritas (Norway), Eidesvik (Shipowner, Norway), MTU CFC Solutions (Fuel cell supplier, Germany), Vik-Sandvik (Ship designer, Norway), Wallenius Marine (Shipowner, Sweden) and Wärtsilä Corporation (Fuel cell supplier, Finland).

Other participants include Izar Construcciones Navales (Steam turbine manufacturer, Spain), Gasnor (Fuel distribution and logistics, Norway) and Sintef Energy Research (Norway).

1.3 Developments in the course of the phase 1

The concepts have been defined, including choice of fuels and type of fuel cell technology. Based on availability, price and storage technology, the main fuels for the first demonstrators will be methanol and natural gas.
Two fuel cell technologies are being explored. MTU’s Molten Carbonate Fuel Cell and Wärtsilä’s Solid Oxide Fuel Cell.

Functional requirements have been defined, based on ship operational profiles and electric grid requirements. A relevant electric grid case model including two different reference cases was studied. The specific properties of each reference case were outlined for:

- Main prime mover for offshore supply vessel with electric propulsion system.
- Auxiliary power supply for a PCTC (pure car truck carrier)

Environmental benefits of using fuel cell versus diesel engine have been modelled and documented, see section 3 below. The extra cost of running fuel cell was also estimated /7/.

The project has developed the rough basic design of fuel cell power packs for two concepts:
- full ship power including propulsion
- auxiliary power

The design has been evaluated with regard to Safety & Reliability. The main issues identified are:

- Methanol liquid leak detection and removal
- Barriers for gas zones
- The requirement for available power in the case of sudden loss of equipment or thrust (dynamic positioning mode)
- Power dump system

Static computer simulations have also been performed, including an initial assessment of the system dynamics. The main challenges considered are the ship operational demands in the dynamic positioning mode, and the implications on machinery systems.
Environmental Studies

The work described in the following was undertaken partly through FellowSHIP, partly as an input to the EU project “Fuel Cell Technology for ships” (FCSHIP 2002-2004) /9/, and partly as a Master thesis /10/.

1.4 Calculated reduced emissions by fuel cells

In the course of FellowSHIP, the environmental benefits of using fuel cell versus diesel engine have been modelled and documented for two ship types; main power production for offshore supply vessel and auxiliary power for pure car/truck carrier, see Table 1.

A Fuel Cell powered ship (LNG or methanol) will have zero emission of nitrous oxides, sulphur oxides, particulate matters and almost 50% reduction in CO2 emissions. A future Offshore Supply Vessel with fuel cells for main power will have yearly reduction potential of /8/:

- 180 tons NOx - equal to 20.000 private cars
  (Norwegian requirement through Gothenburg protocol: max. 156.000 tons in 2010)
- 33 tons SO2
  (Gothenburg protocol: max. 22.000 tons in 2010)
- 4 tons PM
- 4755 tons CO2

For an offshore supply vessel with conventionally machinery running on gas instead of diesel, the CO2 and NOx emissions are reduced by about 24% and 90%, respectively. In addition, the specific fuel consumption will be reduced. The CO2 and NOx reductions depend on the engine load, which basically is a function of the vessel operation mode. The operation mode with highest reduction potential is the transit mode. In this mode, the CO2 and NOx reductions are 26% and 91% respectively. The variation in emission reductions between the operating modes is due to the non-constant difference in specific fuel consumption between gas and diesel operation at the different engine load levels.

Compared to gas piston engines, the installation of fuel cells will reduce the CO2 emission additionally by about 20% due to increased engine power efficiency. For the fuel cell case, the emissions of other exhaust compounds will be negligible. Assuming that the ships operate with the same annually operation profile and energy needs, the calculated total CO2 emission will be reduced by 44%, and the other compounds by close to 100%.

The total yearly reduction potential by using fuel cell is illustrated in Table 1, assuming that CO2 emissions are reduced by about 20% for the gas case and 44% for the diesel case.
<table>
<thead>
<tr>
<th>Case</th>
<th>NOx (ton)</th>
<th>SO₂ (ton)</th>
<th>PM (ton)</th>
<th>CO₂ (ton)</th>
<th>Fuel (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Truck Carrier</td>
<td>6.4</td>
<td>0.6</td>
<td>0.1</td>
<td>206</td>
<td>27</td>
</tr>
<tr>
<td>Supply vessel</td>
<td>180</td>
<td>33</td>
<td>4</td>
<td>4755</td>
<td>585</td>
</tr>
</tbody>
</table>

*Table 1 - Total yearly reduction potential by using fuel cells for two different vessel types.*

Note that emission of other exhaust compounds such as e.g. CO, N₂O, NMVOC will also be reduced, however these elements have not been included in our modelling.

### 1.5 Comparative life cycle assessments

Life Cycle Assessment (LCA) methodology was used to investigate the potential environmental benefits of using fuel cells for auxiliary power on a passenger ship servicing the Oslo-Kiel line /11/.

It is important to recognise that the results presented herein are based on several assumptions made in the course of the work.

A Life Cycle Assessment identifies areas where efforts should be concentrated in order to optimise the environmental performance of the system. It also shows how environmental burdens may be shifted between different life cycle stages as a result of new technology or isolated optimisation of one part of the system. Together with other decision making tools, LCA may provide input to the selection of one technology before another.

The goal and scope of the studies were to explore and assess the environmental impact of use of Solid Oxide Fuel Cells with Gas Turbines (SOFC-GT) in maritime applications compared to conventional diesel engine technology, from manufacture, through the operational phase to the disposal of the units.

The fuel alternatives selected for the application of SOFC onboard the ship was /12/:

- Liquefied Natural Gas (LNG)
- Imported from outside Europe
- Transported by pipeline and liquefied onsite
- Produced in Norway from North sea gas
- Sulphur free car diesel (< 10 ppm sulphur content)

The end-of-life options are studied qualitatively as disposal and recycling mechanisms are still being explored for this emerging technology.

The LCA was performed using the software tool SimaPro, which is based upon a data base of energy and material inputs and associated environmental impacts of a range of processes. The data base is supplemented with data specific for the manufacture and operation of SOFC-GT, and with data for the fuel supply options described in the FCSHIP programme. The LCA has been conducted in accordance with the ISO 14040 standards /13/.

All SOFC-GT scenarios have approximately 35-90% better environmental performance (compared to conventional diesel engine technology run on low sulphur fuel) in the three selected impact categories. LNG supply via Norway has the lowest contribution in all impacts categories considered, approximately 60% lower global warming potential, 85% lower photochemical oxidation and 90% smaller contribution to acidification. This is mainly due to fewer and shorter transportation legs in this scenario.

It is the SOFC-GT operation phase that contributes the most to the global warming category, whilst fuel supply is most important in the photochemical oxidation and the acidification category. This means that if the environmental performance of the system is to be optimised on greenhouse gas emissions, efforts should concentrate on the operational stage; however if photochemical oxidation or acidification are in focus, the fuel supply stages are of importance.

Sensitivity analyses show that neither increase in life-time of the SOFC nor the fuel efficiency have any significant influence on the results.
Conclusions

The FellowSHIP project phase 1 included concept definitions, calculation of environmental performance, indications to cost of fuel cell systems, initial work to the challenges in marinisation of fuel cells, development of basic design of fuel cell systems for auxiliary and main power including electro & automation systems, and analysis of safety & reliability of the concepts developed. The FellowSHIP project phase 1 has been successful with no immediate technical showstoppers identified.

Our work indicates that fuel cells are an interesting technology for ships, and will significantly improve fuel & environmental performance during operation compared to gas/diesel combustion machinery. Life cycle studies were used to compare fuel cells with conventional technology in a cradle-to-grave perspective. The results show that fuel cell technology offers 35-90% improved environmental performance.

Our results clearly illustrates that in a future perspective, fuel cells will be a promising technology for ships.
References


/4/ Environmental Protection Agency (EPA), Control of Emissions of Air Pollutions from Non-road diesel Engines and Fuel; Proposed Rule, Volume II, May 2003.


/7/ Endresen, Ø. & Tronstad, T., Cost calculations of fuel cells in ships, FellowSHIP project report no. 1-1.3C-D-2003-01

/8/ Endresen, & Tronstad, T., Emission reductions by fuel cell ships, FellowSHIP project report no. 1-1.3B-D-2003-01

/9/ Pretlove B., Garmann C., Tronstad T., Life Cycle Assessment of Maritime Fuel Cell Applications, EU project no. G3RD-CT-2002-0083 (FCSHIP), report no. DTR-4.4.3-DNV-06.2004

/10/ Reenaas, Marte, Solid Oxide Fuel Cell Combined with Gas Turbine versus Diesel Engine as Auxiliary Power Producing Unit onboard a Passenger Ferry, NTNU Master Thesis 2005.

/11/ Garmann C., Pretlove B., Tronstad T., Environmental benefits of maritime fuel cells in a life cycle perspective, ENSUS 2005


Transport fuels for the future – the long-term options and a possible development path

Max Åhman, Gunnar Modig, Lars J.Nilsson

Energy and Environmental Systems Studies, Lund University
Gerdagatan 13, 223 62 Lund, Sweden
Max.ahman@miljo.lth.se

Abstract

The aim of this paper is to review the prospect for large-scale automotive fuel and feedstock options and draw some conclusions regarding short and medium-term policy. We are looking at 10-50 year perspective and a robust/flexible strategy based on carbonaceous feedstock that could act as a bridge supporting the long-term development of zero emitting fuel cell or electric vehicles but would not be dependent solely on a specific technical breakthrough. Due to mainly the technology path dependence and the low cost, fossil based fuels will dominate both the medium-term supply and the long-term development of alternatives. This will favor alternative fuels compatible both with fossil and renewable feedstock. Methane is identified as a possible bridge between what is short-term available and long-term possible. Gasification is another future key technology in this transition path that enables a relatively flexible transition to hydrogen, DME, methanol or even F-T fuels in the future. The long-term air quality and CO₂ reduction targets together with the cost development of advanced technologies will eventually determine whether future transport fuels will be based on solar or carbonaceous feedstock.

1 Introduction

Concerns for energy security and environmental protection have been the main driving forces for research and development efforts into new vehicle technology and new fuels, but economic restrictions and market trends have so far, in most countries, hindered the introduction and diffusion of fundamentally new vehicle technologies and alternative fuels. The transport sector is far away from meeting any set reduction targets for greenhouse gases and a continuing growing demand for transport services, high costs for carbon dioxide neutral fuels, and a slow market development for energy efficient cars, makes the transition to a sustainable transport sector seem difficult today.

1.1 Transport energy use today and tomorrow

The global transport sector use approximately 70 to 90 EJ energy per year. In OECD countries, 97% of the transport sector uses petroleum-based fuels. Biomass based fuels (mostly ethanol) currently accounts for less than 1% of total transport energy use within the OECD.

---

1 70 to 90 EJ/year reflects the most estimates. Generally, the transport sector uses about 22 to 25% of the worlds total energy use of ~370-400 EJ/year (IPPC 1996, IEA 2003).
The energy use within the transport sector is expected to continue to grow the coming years. According to World Energy Outlook, global energy use within the transport sector will grow from current estimate of 80 EJ/year to 140 EJ/year in 2030 (IEA 2004a). These numbers are uncertain but give an approximate range of the current and future energy use.

The long-term CO₂-reduction targets for society vary but is usually set around -50% in 2050 and -90% to 2100 from current emission levels, see IPCC (1996). These cuts are necessary for stabilizing the atmospheric CO₂ levels at 550 ppm or below. The dramatic required cuts in CO₂ emission will lead to a high demand and strong competition for renewable energy sources. As the transport sector seems to have the most costly way of reducing CO₂-emission (Gustavsson et al 1995) it has been suggested that the reduction target for this sector should be less stringent than for other sector in society (Kågesson 2001) or that the transport sector should wait until high tech solutions such as PV-cells and fuel cell cars become available (Azar et al 2003). Another way of looking at it is that the high willingness to pay in the transport sector creates a political room of maneuver for promoting more expensive, carbon-neutral fuels.

1.2 Alternative fuels as a long-term solution to CO₂ mitigation

Hydrogen and electricity from solar, hydro, or nuclear power are inherently zero emitters of CO₂ as essentially no carbon enters the life cycle. The hydrogen/electricity options have also the major benefit of being zero emitters of all other air pollutants when used in an electric of fuel cell car. All biomass-based fuels have the potential to be zero, or close zero, net CO₂-emitters over a full life cycle. However, depending on how the biomass is produced, the conversion route taken, and the input fuel needed, the net CO₂-emissions can vary substantially; see IEA 1999 for an overview. Using a fossil feedstock with CO₂ sequestration, only hydrogen has the potential to become a zero CO₂-emitting fuel.

A strict long-term CO₂-reduction target together with strict air quality measures can force solar hydrogen and renewable electricity to the automotive market. Although zero emitting vehicles using solar energy might be necessary for the future, we think that a transition period must involve other low-carbon gaseous or liquid fuels that are not based on dwindling conventional oil-resources. This calls for a strategy that does not exclude this future shift but is neither dependent on e.g. the successful development of fuel cells, solar power or high energy density batteries for electric vehicles (EVs).

1.3 Aim

The aim of this paper is to review the prospect for the most promising large-scale automotive fuel and feedstock options and outline possible development paths based on what alternative fuel/feedstock combinations are available today. We are thus looking at 10-50 year perspective and a robust and flexible strategy based on carbonaceous feedstock that could act as a bridge supporting the long-term development of zero emitting vehicles. Robust in the sense that it has a strength in a broad resource base and flexible in the sense that it can adapt to new, different, or changing requirements.

The analyzed carbonaceous feedstock includes wood, starch/sugar, and fossils. Biodiesel from vegetable oils is excluded, as this feedstock is too limited on a global scale. Small-scale biogas derived from waste streams have no major potential in itself but is compatible with natural gas (both ~95% methane) and is thus included indirectly here as part of a suggested transition strategy.
2 Transport energy supply – technical assessment

The basic factors determining the long-term success of alternative fuels is in this paper assumed to be the potential availability and the potential cost, which can be narrowed down to the technical and physical availability of feedstock, possible future fuel-vehicle combinations, available production facilities and the production cost.

Figure 1 below outlines the different conversion routes explored in this paper from carbonaceous feedstock to usable automotive fuels. The key conversion technologies that are expected to play a significant role during the coming 50 years are thus hydrolysis & fermentation, gasification, steam reforming and CO₂-sequestration.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Conversion processes</th>
<th>Auto fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>Starch &amp; Sugar</td>
<td>Fermentation</td>
</tr>
<tr>
<td></td>
<td>Acid hydrolysis or Enzymatic hydr.</td>
<td>Ethanol</td>
</tr>
<tr>
<td>Woody biomass</td>
<td>Thermal gas. Syngas</td>
<td>Hydrogen Methanol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DME</td>
</tr>
<tr>
<td></td>
<td>Steam reforming (only n-gas)</td>
<td>Fisher-Tr</td>
</tr>
<tr>
<td>Fossils with seq</td>
<td>Unconventional oil, n-gas &amp; coal</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Conversion routes for automotive fuels from carbonaceous feedstock.

2.1 Feedstock resources

The availability of an alternative fuel is in this paper defined as enough potential feedstock resources for the fuel to become a contender on a global scale and a conversion technology that makes the fuel technical possible and affordable. In Table 1 follows an overview of feedstock availability assessments and a brief discussion on some major assumptions.

Table 1. Global carbonaceous feedstock resources.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Biomass (EJ/Year)</th>
<th>Fossil energy (EJ)</th>
<th>Oil Conv.</th>
<th>Oil Unconv.</th>
<th>Natural gas Conv.</th>
<th>Natural gas Unconv.</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current use</td>
<td>33-55</td>
<td>Reserves</td>
<td>6004</td>
<td>5108</td>
<td>5454</td>
<td>9424</td>
<td>20666</td>
</tr>
<tr>
<td>Future estimated</td>
<td>270-450</td>
<td>Resources</td>
<td>6071</td>
<td>15240</td>
<td>11113</td>
<td>23814</td>
<td>179 000</td>
</tr>
</tbody>
</table>

Sources: (Turkenburg 2000; Hoogwijk et al 2003; Rogner 2000).

Biomass

Theoretically 2900 EJ/year of biomatter could be harvested but typically 270 to 450 EJ/year is considered sustainable available, see Table 1. Current bioenergy use is estimated to 33 to 55 EJ/year. Hoogwijk et al. (2003) estimates that 38 EJ is traditional.
use and only 7 EJ is use of modern biomass. With assumed conversion efficiencies of 50 to 70%, the potential biomass correspond to 130 to 310 EJ/year of transport fuel.

The major biomass feedstock in all future estimates is woody biomass from dedicated energy plantations but cellulose from waste streams and residues from forestry will also contribute. Starch and sugar-rich plants do not seem to have the large-scale global potential and is more seen as a regional resource that nevertheless could in specific cases contribute substantially.

The potential for future biomass availability rests on a number of assumptions including the development of dedicated energy plantations and that the inherent land use conflict between food production and biomass for energy purposes be resolved. In the estimates in Table 1, this is accounted for and partly responsible for the varying numbers. As an example, in (Hoogwijk et al 2003) the estimates of available biomass from surplus agricultural land varies between 0 to 988 EJ/year

Fossils

The physical availability of fossils is finite but exactly how much of the resources hidden in the earth’s crust that could be utilized have been debated. A reserve has typically been defined as “occurrences that are identified, measured and at the same time known to be technically and economically recoverable” (Rogner 2000). However, a resource is defined as “occurrences with less certain geological assurance and/or with doubtful economic feasibility” (ibid). Oil companies usually cite a reserves-to-production ratio of 20 to 40 years. This has over the years misled some to believe that we are running out of oil, but the definition of a reserve is dynamic and changes overtime as a result of technological advances and economic incentives. With better extraction technology more resources will become economically feasible and are thus transformed to reserves.

In Table 1, the estimates by Rogner (2004) on reserves and resources for conventional and unconventional fossils are given. There is no immediate or even long-term shortage of fossil material for energy use. However, most analysts are aware of that no more large resources of low cost crude oil will be found and that the cost of extracting fossil energy will rise in the future (not necessarily the price). Natural gas, coal, tar sands, oil shale, and other low grade resources are still relatively abundant and a huge amount of these resources can become available at costs not much higher than the average oil price the last 15 years, that is 22 to 30 dollars/barrel oil equivalent (ibid).

2.2 Conversion processes for carbonaceous feedstock

Ethanol by fermentation

Fermentation is used for producing ethanol and can use any biological feedstock that contains sugar (e.g. from sugar cane or sugar beets) or materials that can be converted into sugar such as starch or even cellulose. Ethanol production from the fermentation of sugar by yeast has been known for thousands of years. Starch from cereals like corn and wheat can relatively easily be converted into sugar and then fermented in a similar way as sugar. The organisms and enzymes necessary for conversion of starch and sugar are commercially available and used on large scale already. Cellulose is more difficult as raw material because it must be broken down into sugars through a process called saccharification. Chemical and biological saccharification processes are under

---

2 In Hoogwijk et al (2003), the total biomass energy supply varies between 33 and 1135 EJ/year.
development. In the chemical route (acid hydrolysis) cellulose is treated by chemicals (e.g. sulphuric acid) in one or two steps for getting five- and six-carbon sugars that can finally be fermented. Another possibility is to use special enzymes, which can “chop” the cellulose molecules into sugar (enzymatic hydrolysis). Extensive research, especially on enzymatic hydrolysis, is ongoing in several countries.

Enzymatic hydrolysis is the most promising conversion route for the future in terms of potential cost and efficiency, but this technology is still under development and not ready for commercialization. Acid hydrolysis is relatively well known and could be available today but is not seen as a competitive route in the long-term.

Syngas from thermal gasification or steam reforming

Gasification is a process that converts carbonaceous material through a process involving partial oxidation with air or oxygen into a syngas consisting mainly of hydrogen and carbon monoxide. Contrary to combustion, the deficit of oxygen in the gasifier reactor does not lead to carbon dioxide and water, which are the usual end products from oil and coal combustion. The syngas can be used in two ways. By using a combination of gas turbine and steam turbine (so called combined cycle) it is possible to generate more electricity compared with only the steam turbine cycle. Another possibility is to use the syngas as chemical building blocks from which a number of chemicals can be produced via synthesis. The end products can be fertilizers or energy-rich products like hydrogen, methanol, methane, Fischer-Tropsch diesel (F-T diesel) or dimethylether (DME) which all can be used as motor fuels. Today only F-T diesel is used as fuel on small scale and limited production from coal gasification exists.

A vision put forward is the creation of a “biorefinery” which, like present oil refineries, could produce a wide range of products including motor fuels but also more advanced chemical products or other energy products. The basic rationale is that the original feedstock could be used much more efficiently and that the economics would, if all the outputs find a market, be advantageous. Polygeneration of heat, electricity and fuels in a “once-through process” has been suggested by Williams (2000). Here syngas is passed once through the reactor to produce a fuel and the unconverted syngas is burned to produce electricity in a combined cycle (trigeneration). Trigeneration offers a technical opportunity to produce fuel from syngas (methanol or hydrogen) and to use part of syngas to fuel a cogeneration plant (heat and electricity) would lower the cost substantially as the syngas does not need to be recycled (ibid).

The least costly way of producing syngas is by steam reforming of natural gas and in combination with CO₂ sequestration this is forwarded as an alternative for the future, see below. Producing advanced fuels from natural gas derived syngas without CO₂ sequestration has the drawback (apart from not being CO₂ neutral) that it may be less costly and more efficient to use the gas directly in compressed natural gas (CNG) vehicles.

Sequestration of CO₂ from fossil feedstock

Fossil feedstock can be used for producing CO₂-neutral transport fuels if the process is complemented with CO₂-sequestration, which includes separation, transport and final storage of the CO₂. Storage of CO₂ is already being done in depleted gas and oil fields but the assessed storage capacity in these abandoned fields varies greatly and is probably limited in the long-term. The large-scale and long-term CO₂-storage is to be found in saline aquifers and deep into the oceans, but this technology is still on a premature level
of development and many uncertainties remain as to whether the sequestered CO$_2$ will remain were it is put or the final cost (Williams 2000).

The scale of the “CO$_2$-source” is of significance. It is not economically or technical possible to sequester CO$_2$ from automobiles or from small facilities at e.g a pump station. The scale for making this alternative reasonable requires typically CO$_2$-rate of 10kg/second, which is comparable to the emissions from a coal power plant of 500 to 1000 MW (Azar et al 2003).

The most realistic and near term conversion route including CO$_2$-sequestration, both from an economic and technical view point, is hydrogen production from steam reforming of natural gas. Hydrogen production from gasification of coal or/and biomass is also possible but more complex and costly (Williams 1998). The cost of carbon management in these alternatives depends strongly on whether the CO$_2$ is sequestered in a depleted gas field or in dedicated CO$_2$-storages such as e.g saline aquifers. In the least costly alternative, hydrogen is produced at the gas field and the CO$_2$ is directly sequestered.

### 2.3 Compatibility with vehicles and fuel infrastructure

Compatibility with the existing or future vehicle fleet is necessary. It’s no coincidence that ethanol is the currently favored alternative fuel due to the almost perfect match between current internal combustion vehicles (ICEVs) and ethanol as a fuel. The other fuels discussed all require changes to the vehicles, the supply infrastructure, or both.

The internal combustion engine can be adapted, with minor costs, to ethanol, methanol, methane$^3$ (CNG or biogas), hydrogen and DME. F-T fuels need no adaptation. Several of the mentioned fuels have already been available on the market such as ethanol, methanol (M85), CNG/biogas. Low blending (<10-15%) is also possible as a “soft” strategy for introducing ethanol and methanol. Vehicle development will to some extent influence the desired fuel. If fuel cell vehicle comes to market as a competitive solution, this will narrow down the fuel selection to hydrogen and/or methanol.

Distribution of the fuel to the engine is a more difficult problem. Here, the difference is to be seen between liquid and gaseous fuels. Liquid fuels (ethanol, methanol, F-T diesel) could use the same modular distribution structure as petrol and diesel (tankers, trucks, pump stations, and fuel tanks). For gaseous fuels, there is a need for a more centralized organization of pipelines supplying the gas. However, the existing natural gas infrastructure can be used as a transition strategy from natural gas based to renewable hydrogen, see Ogden (1999), easing the “chicken or egg” problem. There is also a need for compressing the gas in the vehicle at high pressure adding both cost and energy losses. DME needs to be pressurized to ~5 bars, methane to 200 bars whereas as hydrogen needs to be stored at 300 to 350 bars in order to give the vehicle an acceptable range. Storing hydrogen under low pressure in nanofibre structures is a possible future solution but so far development this technology has not been demonstrated and the feasibility remains highly uncertain.

The need for costly new infrastructure and new vehicles should not be overemphasized. Ethanol, methanol, and F-T diesel poses no major technical obstacles to future use in

---

$^3$ Methane is used as a proxy for natural gas and biogas that contains mostly methane (>95%). The vehicles (CNG) are relatively flexible regarding exact the methane content.
vehicles whereas the gaseous fuels, methane, DME and hydrogen puts a demand on technical development, especially of high pressure vessels for onboard storage.

3 Costs

The interesting cost aspect here are the future costs that could be attained if development is successful. In Table 2 is an overview of cost estimates presented.

Table 2. Estimated production costs

<table>
<thead>
<tr>
<th>Cost assessments</th>
<th>Current technology</th>
<th>Future estimates</th>
<th>Distribution costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol/Diesel</td>
<td>4 – 6 USD/GJ</td>
<td>8-11 USD/GJ</td>
<td>3.5 – 3.9 USD/GJ</td>
</tr>
<tr>
<td>Ethanol starch/sugar</td>
<td>15-20 USD/GJ (Beet)</td>
<td>15-20 USD/GJ (Beet)</td>
<td>–4,2 USD/GJ</td>
</tr>
<tr>
<td></td>
<td>8-10 USD/GJ (Cane)</td>
<td>8-10 USD/GJ (Cane)</td>
<td></td>
</tr>
<tr>
<td>Ethanol cellulose</td>
<td>10-15 USD/GJ</td>
<td>6-9 USD/GJ</td>
<td>–4,2 USD/GJ</td>
</tr>
<tr>
<td>Methanol (cellulose)</td>
<td>11-13 USD/GJ</td>
<td>7-10 USD/GJ</td>
<td>–4,6 USD/GJ</td>
</tr>
<tr>
<td>DME (cellulose)</td>
<td>11-13 USD/GJ</td>
<td>7-10 USD/GJ</td>
<td>6.2 – 8.1 USD/GJ</td>
</tr>
<tr>
<td>Fisher-Tropsch (cellulose)</td>
<td>–20 USD/GJ</td>
<td>–13 USD/GJ</td>
<td>3.5 – 3.9 USD/GJ</td>
</tr>
<tr>
<td>Hydrogen cellulose</td>
<td>10-14 USD/GJ</td>
<td>5-8 USD/GJ</td>
<td></td>
</tr>
<tr>
<td>from n.gas &amp; coal with seq.</td>
<td>n.a</td>
<td>9-11 USD/GJ (coal)</td>
<td>8 – 15 USD/GJ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-6 USD/GJ (gas)</td>
<td></td>
</tr>
<tr>
<td>solar power</td>
<td>n.a</td>
<td>18 to 28 USD/GJ</td>
<td></td>
</tr>
</tbody>
</table>


The Rotterdam price of petrol has varied around 7 USD/GJ in 2003 but in a longer perspective, the price has varied between 4 and 8 USD/GJ (BP 2004). The average cost of extracting the fossils from the earth will rise in the future, but not much higher than current selling prices (Rogner 2000). However, the price for petrol and diesel is expected to rise to 8 to 11 USD/GJ in the longer-term (Turkenburg 2000). Crude oil prices have long been hovering around 20 to 30 USD$_{2004}$/barrel but have lately peaked up to 50 USD/barrel. A crude oil price of 50 USD/barrel translates to 8,8 USD/GJ (add to this the cost of refinement to get the petrol cost). In the oil crises of 1979, crude oil prices peaked at 80 USD$_{2004}$/barrel (BP 2004).

The long-term cheapest alternative seems to be ethanol from cellulose, but these estimates all depend on the successful development of enzymatic hydrolysis. Methanol and DME have, approximately, the same future cost between 7 to 10 USD/GJ, where the lower values depicts large scale manufacturing in ~2000MW facilities. F–T fuels is inherently ~40% more expensive than methanol/DME according to Hamelninck et al (2004).

Hydrogen costs range between 5 and 28 USD/GJ in the estimates, depending on from which feedstock it has been derived. Cellulose is the least costly with a future cost as low as 5 USD/GJ. This low cost is dependent on the same technical development as future methanol, DME and F-T fuels (gasification). Hydrogen from natural gas or coal with sequestration also offers an interesting alternative. The cost of natural gas derived hydrogen could also come as low as 5 USD/GJ largely depending on the low cost of
natural gas and a simple well-known production technique (steam reforming). Here, it is assumed that the hydrogen is produced at the gas field and that the CO\(_2\) can be sequestered directly. The higher costs for coal stems from the need to transport and to sequester the CO\(_2\) in aquifers (Williams 1998).

Given the major uncertainties in these cost estimates, it can be concluded that ethanol, methanol, DME, and hydrogen from cellulose and fossils with sequestration all could become competitive with future petrol and diesel. The only fuel that seems too expensive is ethanol from traditional sugar/starch (note that this is on a global scale), and solar powered hydrogen. F-T fuels seem also to have an inherent cost penalty and will unlikely be competitive in the long term.

One key assumptions underlying the cost reductions above is that cellulose biomass will be produced competitively at a cost of 1,5 to 2 dollars/GJ as compared to approximately 3 dollars/GJ today. This requires using modern technologies and dedicated plantations as well as international biofuel markets for bringing costs down. In most studies cited above, cost reductions that stems from learning by doing have been assumed. This requires substantial “learning” investments often dwarfing previous R&D investments in a, at the time, non-competitive technology (Rogner 1998, Åhman 2003).

Table 1 also includes estimates on the cost of fuel distribution. These are the long-term cost for new fuel infrastructure thus including sunk cost in current fuel infrastructure. The cost for supplying the fuel usually represents around 30 to 45% of the total cost of delivered fuel. All fuels except F-T diesel carry a cost penalty for the distribution compared to conventional fuels. Ethanol can be supplied at almost the same cost as petrol and the cost of supplying methanol is 30% higher than for supplying petrol. A more pronounced costs penalty comes with gaseous fuels that need to be supplied under pressure. For hydrogen, the few assessments available on the cost of supplying hydrogen to a fuel cell differ between 8 to 15 USD/GJ. DME is also in gaseous form but needs a lower pressure than hydrogen and the cost is therefore also less; between 6 to 8 USD/GJ.

4 Development paths for bridging short-term opportunities and long-term visions

4.1 The long-term options

Electricity from solar or nuclear power

Assuming stringent long-term CO\(_2\)-emission and air quality targets, the fuel options will be hydrogen from renewable electricity used in zero emitting fuel cell vehicles or, if battery development surprises us all, electric vehicles fuelled with renewable electricity. Solar electricity has the technical potential to replace all future use of fossil energy. However, the success of solar power rests on the development of photovoltaics and especially major cuts in the production cost before becoming an alternative on the market. Nuclear power can also make a major contribution but faces a number of problems including, weapons proliferation, accident risks, and waste management. Cost is also an issue for nuclear facilities.

Using electricity or hydrogen derived from electricity requires the development of either fuel cell vehicles or high energy-density batteries. High hopes were placed in Lithium-polymer batteries in the mid 1990s, especially by the company 3M/Hydro-Quebec, but hopes vanished as development targets were not reached and the joint venture between
3M and Hydro-Quebec was dissolved. The French company SAFT and Japanese Panasonic continues battery development but aims at the hybrid vehicle market instead requiring high power-density batteries, not high energy-density batteries. The continued development of advanced high energy density batteries will have to rely on the home electronics market as a driver.

Fuel cells are a very promising technology but the barriers facing the technology in terms of development needs have often been underestimated by companies and governments. This is partly due to the rapid development of fuel cell technology that took place in the mid-1990s, driven by the Canadian company Ballard, when fuel cells were developed from an item at the research lab to functioning demonstration vehicles in 5 years. Since then, development has been ongoing in a more normal pace. The major issue that needs to be solved is the cost. The cost of a fuel cell system needs to come done to approximately 50 USD/kW from current levels of 1500 to 3000 USD/kW if to compete with the internal combustion engine (Åhman 2003).

Gasification of biomass

Biomass derived hydrogen can also become a future zero emitting fuel. Other biomass-derived fuels such as methanol, ethanol, DME and F-T fuels might also become long-term winners if emissions of ozone precursors (NOx, HC) and PM could be kept within acceptable limits. The future available biomass has the potential to replace petrol/diesel in the transport sector if used only here. However, it is doubtful whether all the potentially available biomass will be used in the transport sector, as CO₂ mitigation with biomass usually is more cost efficient in other sectors such as heating.

A future biomass derived fuel must come from woody biomass if to contribute substantially. This narrows down the options to syngas derived fuels via gasification or the successful development of enzymatic hydrolysis for producing ethanol from cellulose. In the choice between a conversion routes from gasification compared to enzymatic hydrolysis followed by fermentation we think that gasification holds a number of advantages when it comes to flexibility and technology risk. Gasification not only applies to biomass-derived fuels but also open up for fossils like coal or natural gas combined with sequestration. Syngas can also be produced from steam reforming of natural gas. From syngas it is possible to manufacture several fuels such as methanol, methane, hydrogen, and F-T fuels.

Gasification of biomass has been tried in pilot scale (e.g. Värnamo in Sweden). At present no private actors are willing to finance the further development and demonstration efforts to bring biomass gasification to a commercially ready technology as the revenues from power generation or motor fuel cannot justify the capital investment.

Biorefineries or polygeneration has been suggested as a way to making large-scale gasification of biomass (and coal) economically and technically attractive. However, a polygeneration facility is a very complex and capital-intensive process. The balance between the different “outputs” cannot be chosen freely and, once built and running, this balance is only changed at high costs. This inflexibility poses a major risk for business requiring stabile markets for all outputs. The coming years, polygeneration facilities will only be built in countries with a strong government role, such as China, and be based on the gasification on coal and not biomass. Recently some gasification plants of the trigeneration type have been built at oil refineries. Residual oil products like asphalt are gasified and converted into hydrogen, electricity and steam mainly for internal use.
These investments are in the order of 1 billion EUR, which necessitates a very high throughput (>2000 t/day) to be competitive.

**Time scales for development**

All the long-term options considered here depend on major development efforts and will not be commercial for a great number of years. The “hydrogen vision” is typically assumed to be possible first after 2050 in a major scale. Biomass-derived fuels through gasification is not a commercial route yet and will need considerable time to develop. The scale and financial risks with thermal gasification of biomass suggest that this technology will be developed only after syngas derived fuels have been proven feasible on the market. In the medium term (the next 50 years!) several fuels based on carbon should be tried and developed for supporting the development of key conversion and vehicle technologies necessary for the long-term alternatives.

As a starting point, the short-term options available today are basically ethanol from sugar/starch, RME from rapeseed oil and methane (natural gas or biogas). RME will remain a niche fuel as the overall potential is too low. For ethanol and methane, vehicles and some infrastructure exist today, and both have an interesting potential. However, the key technologies and the development path for large-scale ethanol is inflexible with regards to feedstock and fuel choice whereas methane offers a possible flexible, low risk path outlined below.

**4.2 Methane as an intermediate fuel and feedstock?**

Methane is the major component in natural gas and biogas and is currently used in CNG vehicles in large parts of the world. Argentina, Italy, New Zealand, United States, Brazil, India and Egypt all have major fleets of CNG vehicles due to an already existing natural gas infrastructure making it relatively easy and low cost to introduce CNG vehicles. In Europe as a whole, CNG vehicles are expected to increase substantially the coming years with the expansion of the natural gas grid (EU 2003).

Starting with expanding the use of natural gas and biogas the coming 5 to 10 years would build up consumer confidence in gaseous fuels, infrastructure and support the further development of high pressure vessel for gas storage in vehicle hopefully bringing costs down. This expansion can be done without excessive costs due to the relatively low cost of natural gas and biogas in countries where a natural gas infrastructure already exist.

Note also that gas as an energy carrier is relatively common in developing countries where the major growth of vehicles is expected to occur and that retrofitting conventional vehicles to gas vehicles is relatively easy and low cost. Switching from petrol/diesel to methane in developing countries would mean a lot to air quality as gas is a cleaner fuel than petrol/diesel with no exhaust cleaning devices (such as a catalyst).

However, after an initial build up period of gas vehicles and the associated infrastructure there is a need to avoid a lock-in to “fossil gas”. The shift from natural gas to renewable sources will not be resource driven as the total feedstock of conventional natural gas is huge, see Table 1. The life-cycle emissions of CO\(_2\) is lower than using diesel/petrol due to the low carbon to energy ratio in natural gas and even lower using renewable biogas (IEA 1999) but eventually stricter CO\(_2\)-emission targets will force the use of CO\(_2\)-sequestration techniques for fossil fuels. For natural gas, this necessitates the production of syngas for CO\(_2\)-sequestration (done by steam reforming). Another alternative is to mandate methane derived from biomass to be included in sold gas. Methane from biomass is either biogas from waste streams or methane from syngas. These both
conversion routes offer a CO$_2$-neutral contribution to the sold methane gas. As soon as syngas derived fuels starts entering the market, there will be opportunities for syngas based fuels derived from thermal gasification of biomass and coal although the original track from natural gas favors hydrogen. Which fuel to produce from this syngas is a matter of vehicle development and CO$_2$-reduction targets.

In conclusion, methane offers an intermediate solution that is both short term available and does not lock out any of the hoped for fuels in the future but instead could help to push development in some key technologies regarding gas storage and possibly gasification.

5 Conclusions

The long-term feedstock options that technically have the potential to supply a growing transport sector with renewable energy are solar-based systems (electricity or hydrogen) and fuels from woody biomass. The most likely long-term fuels are thus solar or biomass based hydrogen and electricity and biomass-based methanol and DME. The currently favored renewable fuel, ethanol from agricultural products, will be an important fuel for many decades (especially if enzymatic hydrolysis develops and enables ethanol from cellulose) but nevertheless a parenthesis in the global energy transport supply.

Due to mainly the technology path dependence and the low cost, fossil based fuels will dominate both the medium-term supply and thus the long-term development of alternatives. This will favor alternative fuels that are compatible both with fossil and renewable feedstock.

Methane from both fossil or biomass origin is identified as a possible bridge between what is short–term available and long-term possible. Syngas production by thermal gasification or steam reforming is another key technology in this transition path and opens up for a relatively flexible transition to hydrogen, DME, methanol or even F-T fuels.

The long-term ambition target for the transport sector and the cost development of some other key technologies, notably photovoltaic, fuel cells, and nuclear, will eventually determine whether future transport fuels will be based on solar or carbonaceous feedstock.

6 References


IEA 2004b. Biofuels for transport. IEA/OECD. Paris


Session 6 – Bio-Energy

Chairman: Erik Steen Jensen, Risø National Laboratory, Denmark
The Future of Biogas Production
H. Hartmann and B. K. Ahring
The Environmental Microbiology/Biotechnology Research Group, BioCentrum-DTU, Building 227, Technical University of Denmark, DK - 2800 Lyngby, Denmark, Tel. +45 45256175; fax: +45 45883276; e-mail: hwh@biocentrum.dtu.dk
Keywords Anaerobic digestion; Biogas; Biorefinery; Integrated concept; Renewable energy; Solid-liquid-separation; UASB reactor

Abstract
Biogas production has usually been applied for waste treatment, mainly sewage sludge, agricultural waste (manure) and industrial organic waste streams. Throughout the recent years the performance of biogas reactors has been increased through a better control of the process and improved reactor design based on a better understanding of the process mechanisms and inhibiting factors. In order to improve the economical feasibility of biogas production, a new concept will take over: biorefinery. The goal of the biorefinery concept is to convert close to 100% of the incoming biomass into energy or valuable by-products. One of the currently investigated biorefinery concepts for biogas production from manure implies the separation of manure into a solid and a liquid fraction and their specific treatment in a UASB (upflow anaerobic sludge blanket) reactor and a CSTR (continuous stirred tank reactor), respectively. The solid fraction can be pre-treated more adequately and each effluent of the two fractions has specific nutrient contents, which will improve its value as a fertilizer product.

1 Introduction
1.1 Renewable energy production on its way
In the end of the last century the production of energy from renewable resources has evolved from a playground of a few companies and research centers to a proven technology. After the oil crisis in the 70’s, several countries initiated programs for the development of renewable energy technology in order to reduce the dependency on oil imports.

In the recent years, further reasons for the needs to find alternatives for the energy supply by fossil fuels have become obvious:

- The necessity of worldwide reduction of CO₂ emissions in agreement with the Kyoto protocol.
- The more and more accepted fact that oil production will reach its peak in a not so distant future while at the same time developing countries like China and India are on their way to multiply their energy demand.
- The start of an era of political and military conflicts based on claims on oil reserves.
Whether the worldwide oil production will have its peak by 2010 or 2030 (Duncan and Youngquist, 1999, Cavallo, 2002), the fact that oil reserves are limited is nowadays getting widely accepted, seen by the fact that even large oil companies start investing in renewable energy production.

Both political frames and the development of more efficient energy production processes will decide how fast the ratio of renewable energy production will increase in the future.

Due to promotion of renewable energy through political actions, Denmark was at the forefront of development, marketing and export of renewable energy from wind and biomass in the 80’s and 90’s. At the moment, other European countries are currently taking over the leading role. Germany is probably today’s most growing market for renewable energy production in Europe as a result of the introduction of the Renewable Energy Source Act (Erneuerbare-Energien-Gesetz, EEG). The EEG, which is in force in its amended form since August 1, 2004, guarantees a fixed price per kWh for electricity produced from wind, biomass, hydropower, and solar and geothermic sources for the next 20 years.

In Germany, the production of biogas will probably be one of the most accelerating sectors of renewable energy production and it is expected to induce the construction of several hundred biogas plants. The amount of renewable energy from biogas will thus undoubtedly raise the incentive to develop more competitive and economically yielding processes for the production of biogas. This is, nevertheless, necessary in order to establish biogas production as a profitable process in large scale, when the subsidies are missing.

Compared to other processes for energy production from biomass, biogas production has the advantage of a reliable technology, which can be relatively easily installed in a decentralized structure. Furthermore, biogas is an efficient energy carrier when combined with CHP (Combined Heat and Power) plants and has its advantages to hydrogen since its energy content per m$^3$ is higher and the direct use of biogas in fuel cells for electricity production looks very promising (Baaske and Trogisch 2004).

### 1.2 Optimization of the biogas process

On a worldwide basis, the biogas process will still have its significance as a robust and easily to establish low-cost technology for the treatment of organic waste. Especially in developing countries like China, India and Africa thousands of simple small-scale reactors are under operation and will still in the future have their benefit of waste management combined with decentralized energy production (Wang and Li, 2005, Yadvika et al., 2004, Omer and Fadalla, 2003). However, these reactors are often running under sub-optimal conditions due to the variation of the following parameters that often make steady-state operation impossible:

- Changes in process temperature due to missing temperature control of the reactor and external heat supply
- Changes in the organic loading of the reactor due to
  - Seasonal/monthly/weekly/daily changes in composition of the organic waste
  - Seasonal/monthly/weekly/daily changes in the produced waste amounts
Optimization of the biogas process has in recent years focused on process control to maintain a well-balanced process of the microorganisms involved, on the acceleration of the process by improvement of reactor design and higher operational temperature and on increasing the biogas yield from lignocellulosic biomass through pre-treatment (Ahring, 1995, Hartmann, 2000). As some achievements can be mentioned the development of reactors with immobilized active biomass like the UASB (upflow anaerobic sludge blanket) reactor, which has made anaerobic treatment of high strength wastewater possible and the UASB reactor to one of the most applied anaerobic reactors worldwide, used for the treatment of industrial wastewaters (Seghezzo et al., 1998). Profound research on the mechanisms of the biogas process has made it possible to run co-digestion of different types of organic waste in centralized biogas plants and to achieve profitable economical operation (Ahring et al., 1992, Hartmann et al. 2002). In Denmark, for instance, centralized biogas plants are based on manure and up to 25% of organic waste with a high biogas potential is added to. The volume of this organic waste is, however, limited Danish Energy Agency (1995) and future biogas plants have to increase their energy yield by running the biogas process more efficient on lignocellulosic biomass and by expanding the variety of biomass used.

2 The biogas concept of the future: Biorefinery

Although huge amounts of manure are available, the operation of Danish centralized biogas plants exclusively on manure is currently not economically feasible due to high transportation costs per m$^3$ compared with the benefit from the biogas yield per m$^3$. A low biogas yield per ton manure is due to two factors:

- The content of organic matter is typically about 5% for swine manure and 8% for cow manure, meaning that 92-95% of each ton is water.

- A large part of the organic content in manure is consisting of lignocellulosic fibers that are recalcitrant to anaerobic degradation.

The benefit of the anaerobic treatment will, therefore, very much depend on the improvement of the process regarding a higher biogas yield per m$^3$ of biomass and an increase in the degree of degradation. Furthermore, the benefit of the process can be multiplied by the conversion of the effluent from the process into a valuable product. Compared to combustion, this concept has the advantage of preserving the nutrients, which can be recycled to agricultural land. In order to show the real benefit of biogas technology, biogas production should therefore always be combined with full recycling of the nutrients.

In order to improve the economical benefit of biogas production, the future trend will go to integrated concepts of different conversion processes, where biogas production will still be a significant part. In a so-called biorefinery concept, close to 100% of the biomass is converted into energy or valuable by-products, making the whole concept more economically profitable and increasing the value in terms of sustainability.
2.1 Biogas production in combination with bioethanol production

One example of such biorefinery concept is the Danish Bioethanol Concept (DBC, International patent WO 01/60752 A1) that combines the production of bioethanol from lignocellulosic biomass with biogas production of the residue stream (figure 1). In this concept the production of bioethanol as liquid fuel for transportation is the central aim in order to increase the part of renewable energy used in the transportation sector, which is in countries like Denmark, for example, the most increasing energy-consuming sector. In order to reduce the costs for the production of ethanol, the novelty of the process is not only a higher sugar release through an improved pre-treatment method and a fermentation of xylose, but also the integration of the treatment of the effluent stream from the fermentation in a biogas reactor (Torry-Smith et al., 2003). The biogas treatment has two benefits: An extra energy yield in the form of biogas and the purification of the effluent stream in the biogas process so it can be used as process water.

![Figure 1: The Danish Bioethanol Concept](image_url)
2.2 Biogas production in combination with separation and use of by-products

Another example is the combination of biogas production from manure with manure separation into a liquid and a solid fraction for separation of nutrients. The separation opens the way for the following benefits:

- The separation of the two fractions lowers the transportation costs when applying on-site treatment of the liquid fraction at the farm site and treatment of the fiber fraction at the centralized biogas plant.
- A more adequate treatment of each fraction, i.e. the liquid fraction in a UASB reactor, and the solid fraction in a CSTR reactor with recirculation of process water, with specific adjustment of the organic loading rate (OLR) and hydraulic retention time (HRT) and specific pre-treatment for each fraction.
- The separation provides specific N- and P- fertilizer fractions that can be further processed to high quality fertilizing products.

It has been recently shown that solid-liquid separation of manure can be successfully applied using either decanter centrifugation or chemical precipitation (Møller et al., 2004). The separation of manure into a solid and a liquid fraction does, furthermore, comply with legislation on nutrient control, which is on its way in Denmark.

In a project financed by the Danish Energy Agency cost-benefit calculations are currently performed on 9 different concepts including solid-liquid separation as pre-treatment on the local farms, solid liquid post-treatment and recirculation of the fiber fraction, wet oxidation of the fiber fraction and treatment of the liquid fraction in UASB reactors. One of the most promising concepts is the treatment of the liquid fraction on the farm-site in a UASB reactor while the solid fraction is transported to the centralized biogas plant where wet-oxidation can be implemented to increase the biogas yield of the fiber fraction (figure 2).

![Figure 2: Solid liquid separation of manure with treatment of the liquid fraction in a UASB reactor at the farm and of the solid fraction in the centralized biogas plant after pre-treatment](image)

The efficiency of this new concept will rely on both the biogas yield of the solid fraction at the centralized plant and of the liquid fraction at the farm site.
3 Treatment of the liquid fraction in UASB reactors

Small units of UASB (upflow anaerobic sludge bed) reactors are the most promising method of choice for anaerobic treatment of the liquid fraction on the farm. The immobilization of the active biomass inside the UASB reactor enables a high flow and a low retention time so that the reactor size can be kept small. Currently only a few investigations have been undertaken on the treatment of the liquid fraction of manure in UASB reactors (Castrillon et al. 2002, Kalyuzhnyi et al., 1998). Recent investigations at DTU show that methane yields of 240 l/kg-VS can be reached for an OLR of 6 kg-VS/m^3/d, but the reactor can be operated stable at OLR of 36 kg-VS/m^3/d with a methane yield of 130 l/kg-VS, corresponding to a methane production rate of almost 5 m^3/m^3 reactor/d. (figure 3).

![Figure 3: Methane yield and productivity versus organic loading rate in UASB reactor](image)

Figure 3 shows on the basis of mass flow of the separation unit and with methane yields usually achieved from swine manure how the increasing separation and the separate treatment increases the methane productivity of the whole system. The methane yield per t of influent delivered to the plant increases from 16 m^3 to 25 m^3, when 75% of all manure supplied to the centralized biogas plant is separated. The methane yield from the liquid fraction is only 10 m^3/t, the productivity per reactor volume, however, is about 10 times higher in the UASB than of the CSTR since the HRT in the UASB system is only 1.5 days compared to usually 15 days in the CSTR.
4 Pre-treatment of the solid fraction

Due to the separation of the fibers, any pre-treatment method to increase the degradation of lignocellulose can be applied more specifically since the treatment has its highest benefit on the fiber fraction. In figure 5 the effect of wet oxidation pre-treatment, which is performed at 170°C, 15 bar pressure, and under addition of oxygen, is shown for raw manure and on manure fibers only. Measurements of the biogas potential before and after wet oxidation treatment show that the wet oxidation treatment had an increasing effect on the methane potential mainly of the manure fibers while the effect was lower on the whole manure. After 14 days of incubation the increase was 98% for manure fibers, and only 23% for whole manure.
Applying the doubling of the methane yield when the separated solid fraction is pre-treated by wet oxidation, the methane yield will increase to 39 m³ per t of treated material (figure 6).

Figure 6  Mass flow, methane yield and methane productivity for the system of manure separation combined with wet oxidation of the solid fraction
5 Conclusion

In order to extend its market position in the future, biogas production has to become part of an integrated biorefinery concept, where up to 100% of the incoming biomass is converted into energy or valuable products. Applying this concept to manure, the separation of manure into a solid and liquid fraction with subsequent treatment in a UASB and CSTR reactor is a very promising way to achieve a significant increase in the economical benefit of biogas systems. Integration of the wet oxidation pre-treatment of the solid fraction leads to a high degradation efficiency of the lignocellulosic solid fraction. Based on these results, the operation of this system should make it economically feasible to produce biogas only from manure. Further refining of the effluents from the process into a high quality fertilizer product would further increase the economy of the concept.

6 References


Black liquor gasification - the fast lane to the biorefinery

B. Rikard Gebart\textsuperscript{1}, L. Westerlund\textsuperscript{2}, A. Nordin\textsuperscript{3}, R. Backman\textsuperscript{3}, B. Warnqvist\textsuperscript{4}, T. Richards\textsuperscript{4}, I. Nohlgren\textsuperscript{1}, L. Olm\textsuperscript{5}, N. Berglin\textsuperscript{5}, L. Troselius\textsuperscript{6} and I. Landälv\textsuperscript{7}

1: ETC, Box 726, SE-941 28 Piteå, Sweden
2: Division of Energy Technology, Luleå University of Technology, SE-971 87 Luleå, Sweden
3: ETPC, Umeå University, SE-901 87 Umeå, Sweden
4: Forest Products and Chemical Engineering, Chalmers University of Technology, S - 412 96 Göteborg, Sweden
5: STFI-Packforsk AB, Box 5604, SE-114 86 Stockholm, Sweden
6: Swedish Corrosion Institute, Kräftriket 23 A, SE-104 05 Stockholm, Sweden
7: Chemrec AB, Floragatan 10 B, SE-114 31 Stockholm, Sweden

Abstract

The modern pulp mill has the potential to be transformed into a biorefinery that produces electrical power, fuels and valuable chemicals at competitive prices in addition to pulp and paper. Estimates that have been made for Sweden indicate that about 30\% of the national need for transportation fuels could be produced from the “black liquor” from pulp making. Black liquor is a mixture of lignin and spent cooking chemicals and can be considered a "green" fuel since the lignin, and other organics in it, originate from biomass (wood), and all the cooking chemicals are recycled to the pulping process. As an alternative to fuel production, electrical power can be produced more efficiently than with current technology and the potential for increased power production is then about 7 TWh/annum for Sweden. The total power production potential has been estimated at about 15 TWh/annum. It is also possible to produce specialty chemicals from the syngas but no estimate on the potential of this alternative has yet been made.

The key to these exciting new possibilities is pressurized black liquor gasification (PBLG). Techno-economical studies at Princeton and in Sweden have shown that both the power and transportation fuels production alternatives are economically competitive with current technologies, including fossil fuel based technology. Motivated by this potential, black liquor gasification is under intense development both in the US and in Sweden.

The main technical difficulties with PBLG are containment material issues, mill integration and gas cleaning. The mill integration of the process is very important since not only the energy in the black liquor must be recovered but also the cooking chemicals must be recycled to the pulping process in a suitable form. This is a challenging task but it also opens up new possibilities to improve the pulping process by taking advantage of the coupling between process parameters and the recycled chemicals composition. Preliminary tests at STFI have shown that it is possible to increase the pulp yield by about 5\% (more paper – same wood) with a judicious choice of process parameters in the gasifier in combination with modifications to the pulping process.

In Sweden a national research program on black liquor gasification was started in 2001
and was expanded and extended in 2004. The program is focusing on computer modeling of the process, detailed studies of the kinetics of carbon conversion and inorganic reactions, on corrosion of materials and finally on integration of the gasification process with the pulping process. In parallel with the research program a development plant with a 20 ton ds/day Chemrec gasifier is under construction at ETC and Kappa Kraftliner in Piteå, Sweden. The development plant will be used for technical development and for long time testing of the process to make assessments of process reliability and material behaviour possible. The development plant will also be used by the research program for full scale experiments and validation of computer models.

The presentation will contain a summary of international activities on black liquor gasification and a presentation of highlights from the eight sub-projects of the research program

**Introduction**

Overall energy use in Sweden is on the order of 400 TWh annually (Statistics Sweden, 2004). Industrial use is about 150 TWh and the pulp and paper industry uses close to 50% of this. The pulp and paper industry is different from most other industries in that most of its energy use is met with fuels that are generated internally as by-products of the pulping process. In chemical pulp mills 40-60 per cent of the wood entering the mill is used as a fuel. Black liquor, which is the most important internal fuel, is generated in the Kraft cooking process, the dominant process for pulp production in Sweden and worldwide.

Black liquor contains most of the organic substances that must be dissolved in order to free the wood fibres. In addition, the major part of the chemicals used in the cook is recovered in the black liquor. It is essential for the economy of the pulping process that these chemicals can be regenerated and recycled to the process. This means that the recovery process must be an efficient chemical reactor while also being able to convert the energy contained in the black liquor to useful heat and power. The long-standing practice has been to perform these tasks simultaneously in one piece of equipment, the recovery boiler, sometimes referred to as the Tomlinson boiler.

The new process, black liquor gasification, aims at improving both functions of the recovery process, by splitting the operation into several pieces of equipment, each optimized for its purpose. The desired reduction of sulphur compounds to sulphides is carried out in the reductive atmosphere in the gasifier. Gaseous hydrogen sulphide is captured in a gas cleaning operation, after which the rest of the product gases, mainly carbon monoxide and hydrogen, can be used either as fuel to a gas turbine for power production or as feedstock to a chemical synthesis plant for production of transportation fuels or specialty chemicals. The pulping chemicals are recovered from the gasifier and gas cleaning operation.

The potential advantages of black liquor gasification include: (1) a high power-to-heat ratio or high yield in conversion of black liquor into motor fuels, (2) flexibility in the preparation of cooking liquors, (3) low emissions, (4) small units in pressurized operation, and (5) safe operation. The major concerns of the pulp and paper industry are that a new recovery process must have a high reliability and a reasonable cost. Reliability can only be proven through mill-scale operation and testing; the costs will depend on the necessary equipment and the resulting material and energy flows in the
mill as well as the cash flow generated by new products.

The gasification of spent cellulose liquor was first proposed as early as 1951 (Whitney, 1951). In the late 1950s and early 1960s, much of the fundamental thermodynamic research on black liquor gasification was carried out (Rosén, 1964).

The latter work was financed by the Swedish pulp and paper industry and led to the construction of a pilot plant. The process was used for regeneration of spent sulfite cooking liquors, but could in principle be used for Kraft black liquors. It was operated at low temperatures, below the melting point of the ash, and it became known as the SCA-Billerud process (Bergholm, 1963). Work on this process was discontinued, although one unit is still in operation (Rounsley, 1995), but renewed interest in a gasification-based recovery process was shown in the 1970s and later led to the construction of a pilot plant based on a cyclone furnace connected to a boiler. In this case, operation above the melting point of the ash was desired (Holme, 1985). Neither of these processes could show any dramatic improvement over the Tomlinson boiler in process operation or economy. However, recent developments have resulted in new processes, e.g. the Chemrec process (described below), which is expected to result in much higher overall efficiency.

**High temperature gasification**

The Chemrec process is a high temperature/high pressure process operating above the melting point of the cooking chemical salts dissolved in the black liquor. Chemrec also has a gasifier operating at atmospheric pressure but this is not suitable for power and fuel generation and thus not described further in this paper.

![Figure 1: Schematic of the Chemrec process for high temperature gasification of black liquor.](image)

The overall process for making power/heat or motor fuels (MF) is presented in block diagram form in fig. 1. The main process blocks are (1) air separation to generate pure oxygen, (2) BL gasification (3) gas purification, conditioning and sulfur recovery and (4) power/heat generation alternatively MF production. Unit (1) and (2) are the same regardless of selected process in process block (4) while process block (3) need to be designed differently for the two cases. Unit (1) is a standard cryogenic air separation plant producing gaseous oxygen for the gasification unit. Certain minor amounts of
Gasification, process block (2) takes place in an entrained flow gasifier with the flame directed downwards. Black liquor (BL) and oxygen are fed simultaneously to a burner system at the top of the gasifier. The ratio between the two flows is controlled to hold the gasifier temperature constant at about 1000 °C. The BL is converted to a raw synthesis gas and a liquid smelt flow and these two product streams leave the gasifier reactor through the bottom outlet. The reactor is lined with a ceramic material which withstands the very corrosive environment created by the hot smelt and the gases.

The hot product gas is cooled in two steps in a quench vessel below the gasifier using recycled condensate as quench media. Between the two steps the liquid smelt, which now has started to solidify, is separated from the product gas. The product gas is cooled to saturation in the second quench step. The salt from the first quench is dissolved in water below the first quench and forms so called green liquor. This is cooled and sent to the pulp mill to be processed back to white liquor, the cooking chemical.

The product gas is cooled in a gas cooler to about 40 °C and sent to gas treatment. The condensate cooled out from the saturated product gas is sent back to the two quench stages. The cooler is also an efficient first gas cleaner which means that entrained particles are washed out of the gas and sent back with the condensate finally ending up in the green liquor.

The aim with process block (3) is to condition the gas and clean it from non-desired components. Among the components which must be washed out are the sulfur components. 50-60% of the sulfur in the BL shows up as sulfur components in the product gas, mainly as hydrogen sulfide. The product gas need to be treated differently depending on what the end product is as can be seen in table 1.

Table 1: Gas treatment before power and motor fuel production.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Power unit in block (4)</th>
<th>Fuel unit in block (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal of S components</td>
<td>Remove &gt; 99.5%</td>
<td>Remove close to 100%; Only traces left in product gas</td>
</tr>
<tr>
<td>Removal of CO2</td>
<td>Minimize removal</td>
<td>Remove 90-95%</td>
</tr>
<tr>
<td>Adjust H2/CO ratio</td>
<td>Not needed</td>
<td>Need to be adjusted</td>
</tr>
<tr>
<td>Sulphur recovery</td>
<td>Needed; S recycle to mill</td>
<td>Needed; S recycle to mill</td>
</tr>
</tbody>
</table>

If the BLG unit is installed to increase power generation from the mill the final process block is a combined cycle unit comprising a gas turbine, a heat recovery section and a steam turbine. If the product gas is converted to a clean syngas to be used for fuel generation then unit (4) is a synthesis unit followed by an upgrading unit to purify the product to the right quality. The synthesis can generate e.g. DME (dimethylether), methanol or synthetic diesel. The gas can also be converted to pure hydrogen. The withdrawal of large energy streams in the form of an automotive fuel need to be compensated for through the addition of extra biomass to the power boiler of the mill.

50-60% of the sulfur present in the black liquor will show up as sulfur components (mainly H2S) in the raw gas. The process has thus accomplished a sulfur split. The green liquor from the quench vessel will be low in sulfidity. The sulfur in the gas can be
recycled separately from the green liquor and therefore the cooking process can be optimized to higher yield through addition of the cooking chemical streams at optimum location in the cooking process (see below).

**Swedish research program**

A focused effort to finally bring high temperature black liquor gasification technology to the market was started in 2004 when a consortium with eight partners joined forces to fund a 3-year research program (“the Swedish BLG research program”) with a budget of 100 million SEK. The partners are the Swedish Energy Agency, MISTRA (research foundation), Vattenfall (utility), Chemrec (technology owner) Kappa Kraftliner (pulping), SCA Packaging (pulping), Södras forskningsstiftelse (pulping) and Sveaskog (forestry). The program consists of two parts, large scale tests in a 20 ton ds/day Chemrec gasifier and a focused research program aimed at removing obstacles for commercialization of the process. The research program have four sub projects oriented towards the gasifier and its sub systems and four sub projects oriented towards integration of the process with the pulping process.

**1.1 Gasifier oriented research**

The gasifier consists of a hot gasification reactor, a quench cooler and sub systems for gas cooling and gas cleaning. In the hot part the organic carbon and hydrogen in the black liquor is converted to a raw gas consisting mainly of steam, CO, H₂, CO₂, H₂S and a molten smelt containing compounds produced from the cooking chemicals in the black liquor. The process parameters that are critical for the performance of the conversion of black liquor into an energy rich gas are the geometry of the gasifier, the oxygen relative to stoichiometric combustion and the design of the burner and oxygen nozzle. It is very time consuming and expensive to make an experimental optimization; hence it is of great interest to develop computer simulation models that can be used for optimization. The model developed within the Swedish BLG research program (Marklund et al., 2005) uses an Eulerian-Lagrangian approach for spray gasification in which individual droplets are tracked and modeled with respect to chemical reactions and interaction with the gas phase. The global effect from the particles on the gas phase is modeled with source terms in each computational cell for the gas phase. The particle model involves sub models for swelling of droplets during conversion, heterogeneous reactions at the droplet surface and homogeneous reactions inside droplets. The model ultimately predicts the carbon conversion and the smelt composition of individual droplets when they leave the reactor that can be used to compute the overall carbon conversion and smelt composition. An example of the gas temperature from a simulation with this model is shown in fig. 2.
The sub models for the droplets involve parameters that can only be determined experimentally. Two of the sub projects in the research program are therefore aimed at fundamental experiments and further development of the sub models. One of the sub projects is dealing with the swelling behaviour of droplets and the kinetics of carbon conversion. The experimental work has been performed in a TGA equipment where it was possible to videorecord the dynamic swelling behavior. Based on the experiments a mathematical model has been developed that predict the swelling behaviour of individual droplets (Wintoko and Richards, 2004). The other research project is focused on the inorganic reactions that govern the smelt composition, and the relation between sulfur in the gas phase (mainly H$_2$S) and in the smelt phase (Na$_2$S). In turn, these relations basically determine green liquor quality in terms of sulfidity and bicarbonate content, and ultimately lime consumption in causticizing (see further below). It was found at an early stage of this project that there is a significant scatter in literature data for some of the crucial thermodynamic data. Hence, the most critical of these data have been re-determined with modern methods and better accuracy than previously to settle the issue about what values to use (Raberg et al. 2003).

In the quench cooler, which is situated immediately downstream of the gasification reactor, water is sprayed into the gas to quickly bring down the temperature to prevent formation of carbonates and to saturate the gas with water vapor. The quench cooler is also designed to separate the smelt from the gas to form an aqueous solution (“green liquor”) that is returned to the mill for conditioning before it is used for a new cycle of pulping. Also in this case computer simulation is an important tool for process optimization and as a tool for problem solving. The model is similar to the gasification reactor model with a Lagrangian treatment of water and smelt droplets and an Eulerian treatment of the gas phase. Examples of use for the model are for optimization of the location and number of spray nozzles and for geometry optimization of the quench.
vessel to give the best possible separation of smelt droplets from the gas phase. Figure 3 shows the velocity distribution in the quench.

![Velocity distribution and path lines in the quench cooler. The inlet is connected to the outlet from the gasification reactor (cf. fig.2).](image)

In the subsequent gas cooling and gas cleaning the gas is further cooled in a counter current condenser so that most of the water vapor is condensed into droplets and so that all the sulfur is removed from the gas. The sulfur is then recycled to the pulp mill, either into the green liquor or into another stream for a modified pulping process. Also for these components computer simulation models makes it possible to optimize the system.

One of the untested components in the gas cleaning system is the counter current condenser that cools the saturated product gas from 220 °C to 40 °C. During the cooling most of the water will condense and flow in the opposite direction to the product gas due to gravity. A model for the condensation is under development. The model predicts the growth by condensation of water vapor on infinitesimal seed particles. Initial tests on idealized geometries have resulted in reasonable results but work still remains on the optimum choice of the number of seed particles and their distribution in space before simulation of the real counter current condenser can be attempted.

### 1.2 Mill oriented research

Before large scale implementation of the black liquor technology will be a realistic alternative to the recovery boiler several questions about integration with the pulping process must be answered. Problems and possibilities related to BLG mill integration which have been identified, are (i) increased causticizing requirement, (ii) removal of non process elements (NPE) and (iii) integration of alternative pulping processes.

Causticizing is an integral part of the chemical recovery at kraft pulp mills, where sodium carbonate is converted to sodium hydroxide by reaction with lime, i.e. forming the pulping liquor, so called white liquor. When introducing black liquor gasification it is likely that more sodium carbonate will be formed from the gasifier than currently from the recovery boiler. This will lead to an increased causticizing demand, i.e. more lime will be needed and larger capacity in the lime mud reburning unit and consequently, an increased fuel demand. The reason for the higher amount of carbonate formation in the gasifier unit is the changed sodium and sulfur
chemistry. In a high temperature, high pressure gasifier about 50% of the sulfur in black liquor will be released to the gas phase, mainly as hydrogen sulfide (H\textsubscript{2}S). In the recovery boiler the sulfur is bound mainly as sodium sulfide (Na\textsubscript{2}S) in the condensed phase. During these gasification conditions the sodium, which would form Na\textsubscript{2}S in the recovery boiler, will form sodium carbonate instead, i.e. increasing the causticizing demand. Liquor-gas contact and reaction with H\textsubscript{2}S and CO\textsubscript{2} in the gas phase forms sodium bicarbonate (NaHCO\textsubscript{3}) which further increases the lime consumption in causticizing. In situ (i.e. direct and auto) causticizing processes offer a solution to this problem by adding a chemical agent to the gasifier to form a salt and thus allow the carbon to be released as carbon dioxide (CO\textsubscript{2}). Several different in situ causticizing processes have been suggested in the literature, the most promising for kraft processes are considered to be titanate direct causticizing and borate auto-causticizing (Nohlgren, 2004). In the Swedish BLG research program the feasibility of borate auto-causticizing combined with high temperature, high pressure BLG will be evaluated.

In addition to causing an increased causticizing demand the separation of sodium and sulfur in the BLG system opens up interesting possibilities for alternative pulping processes, which could result in higher wood yield, and thereby increased profitability for the pulp mill. This is a research area related to BLG mill integration, with synergies between two important research topics in the pulp industry: the search for ways of increasing the pulp yield in chemical pulping and more efficient chemical and energy recovery. The commercial technique for increasing the pulp yield in kraft cooking is to add polysulfide (PS) and/or anthraquinone (AQ) to the pulping liquor. The commercial production of polysulfide liquor is by white liquor oxidation with air or oxygen in the presence of a catalyst and AQ is charged as an additive to the cooking liquor. However, new possibilities for generation of polysulfide liquors opens up when introducing BLG, due to the separation of sodium and sulfur, which makes it possible to create two types of white liquors, one sulfur-rich and one alkali-rich. The sulfur rich liquor is suitable for more efficient generation of PS liquors than current commercial processes. Furthermore, this liquor with a high hydrogen sulfide ion and low hydroxide ion concentration can preferably be used in pretreatment/preimpregnation stage of kraft cooking, so-called ZAP-cooking (Olms and Tormund, 2004), where ZAP stands for Zero effective Alkaline Pretreatment stage. In the most favorable case this pretreatment method in kraft-AQ cooking can give a yield improvement of 3-4% on wood. This leads to a production rate increase or reduction of wood costs. Another advantage of improved yield is the greater flexibility in tailoring the fiber properties. The effect and potential of the new pulping liquors from BLG-systems on cooking performance and pulp quality will be established in the Swedish BLG research program. Process modeling and techno-economic assessment of the new pulping options are also included.

The third research area related to mill integration is the handling and removal of non-process elements (NPEs), e.g. potassium (K), chloride (Cl) and calcium (Ca). NPEs enter the pulp mill with wood and chemicals and accumulate in the pulp mill and cause problems with deposits and corrosion. In a pressurized BLG system the options for controlling the concentrations of both process and non-process substances will differ from those in a recovery boiler system, opening up
possibilities as well as potential problems. For example, the separation of sodium and sulfur opens a better possibility to control the sodium and sulfur balance even at mills with a high degree of system closure. Controlling the build up of NPEs is important for several reasons: (i) operability and availability, scaling leads to more downtime or requires extensive washing, (ii) separation processes that are required will affect the energy balance of the process, (iii) operating and investment cost will be affected. The NPEs that are of main concern are those that are more or less soluble under alkaline conditions and consequently accumulate in the liquor cycle, i.e. chloride (Cl), potassium (K), aluminium (Al), silica (Si) and in the lime cycle, mainly phosphorous (P). Within the Swedish BLG research program options to purge sodium, sulfur, NPEs and ammonia from BLG systems will be evaluated, including technical and economic assessment. Furthermore, simulation models will be extended to include the handling of non-process elements and gases (e.g. K, Cl, NH₃).

Discussion and conclusions

The new high temperature gasification technology that is at the focus of the Swedish BLG-Program is a key technology that can transform pulp mills into bio-refineries that produce pulp and valuable chemicals. The equipment that is needed downstream of the gasifier is available off-the-shelf from several vendors of chemical process equipment but the gasifier is still unproven regarding availability and maintenance costs. The goal of the BLG-program is therefore to eliminate as many as possible of the unknowns that are preventing decision makers to make an informed assessment of the technology.

Based on existing theoretical and experimental results it is clear that the technology has the potential to increase power production up to three times compared to existing recovery boilers. Moreover, the new technology is the only available technology that can be used to refine black liquor into valuable chemicals and fuel for internal combustion engines. Cost estimates for these new fuels (Ekbom et al, 2003) indicate that the price per kilometer in a vehicle (before taxes) will be about the same as for gasoline (before taxes) at the current price level.

The yield for fuel production is about 345 kg methanol per tons of black liquor (Ekbom et al, 2003). The efficiency is about the same for other fuel alternatives, e.g. hydrogen and dimethylether (DME). Hence, a typical pulp mill in Scandinavia that produces about 2000 ton black liquor per day has the potential to produce close to 700 ton methanol per day or about 240 000 ton per year. A very rough estimate of the corresponding sales price for the fuel indicates that it could be between 50.000.000 and 100.000.000 Euro per year (assuming a sales price between 20 and 40 Eurocent per kg).

A very attractive feature of the pulp mill as a starting point for development of a biorefinery is that the infrastructure is already in place. The pulp mill has an advanced logistics system for import of biomass raw material and export of products, experience and know-how about handling of chemicals and also acts as a heat sink for excess heat from syngas production and chemical synthesis. All these factors contribute to making the pulp mill the ideal location for an energy efficient and profitable biorefinery.

Several technical challenges remain before black liquor gasification can be introduced in large scale. One of the key questions is the availability of the process since an unplanned stop in the recovery unit will result in a shut-down of the whole pulp mill. Another
important question is how well the process can be integrated into an existing pulping process and if the pulp yield can be increased.

The availability of the process depends on many different factors but the critical factors appear to be the durability of containment materials, the robustness of carbon conversion and green liquor formation. The key material issue is the durability of the refractory material on the inside of the gasification reactor that must be able to tolerate absorption of e.g. sodium compounds that will lead to material expansion that potentially can generate spalling and structural failure of the refractory. Also the metal that is in contact with 220°C green liquor is an unknown factor that must be studied before a reliable sizing of the green liquor piping system can be made.

Regarding the carbon conversion and green liquor formation several factors are important, e.g. the burner performance, the influence from oxygen-to-fuel ratio and the efficiency of the quench cooler that is supposed to prevent unnecessary formation of carbonates in the smelt that must later be reformed into sulfide through an energy consuming causticizing operation.

The on-going Swedish BLG-program addresses all of these questions and more. In combination with practical experience from the development plant in Piteå and close collaboration with interested pulping companies it is expected that all major scientific and technical barriers to the introduction of high temperature black liquor gasification shall be removed.

An interesting future development that becomes possible once black liquor gasification is in place is to introduce gasification of raw biomass, e.g. wood residues, at the pulp mills in combination with black liquor gasification. The potential for synergy in this case is very large, e.g. could the air separation unit and chemical synthesis plant be shared between the two gasifiers resulting in a better overall economy.

Acknowledgements

This work was made within the Swedish Black Liquor Gasification program, funded by a consortium consisting of the Swedish Energy Agency, MISTRA, Vattenfall AB, Kappa Kraftliner AB, SCA Packaging AB, Södra forskningsstiftelse, Sveaskog AB, Chemrec AB and the County Administrative Board of Norrbotten.

References


Enzymatic hydrolysis and glucose fermentation of wet oxidized sugarcane bagasse and rice straw for bioethanol production

HAAGENSEN F.\(^a\), AHRING B.K.\(^a\)

\(^a\) Environmental Microbiology & Biotechnology Research Group, BioCentrum-DTU, Technical University of Denmark, DK-2800 Lyngby, Denmark
\(^*\) corresponding author, telephone: +45 45 25 61 83, e-mail: bka@biocentrum.dtu.dk

Abstract

Alkaline wet oxidation was used as pretreatment method of sugarcane bagasse (SB) and rice straw (RS) prior to enzymatic hydrolysis and glucose fermentations with \textit{Saccharomyces cerevisiae}. At high enzyme loadings, the enzymatic hydrolysis of wet oxidized sugarcane bagasse (SBWO) resulted in the highest degree of saccharification compared to wet oxidized rice straw (RSWO). However, at enzyme concentrations below 10 FPU/g-cellulose, wet oxidized rice straw showed faster hydrolysis and higher levels of saccharification. Incomplete hydrolysis was found for both biomass suspensions with maximum yields of 73\% and 62\% (of theoretical) for SBWO and RSWO, respectively.

Ethanol yields from simultaneous saccharification and fermentation (SSF) were similar to what would be expected from the enzymatic hydrolysis. Based on this, it was concluded that the results of enzymatic hydrolysis was not affected by feed-back inhibition of the enzymes. The maximum ethanol yields from SSF of SBWO and RSWO were 0.39 g-ethanol/g-glucose and 0.31 g-ethanol/g-glucose, respectively.

Similar ethanol yields of SBWO and RSWO was seen at enzyme loadings of 25 FPU/g-cellulose when separate hydrolysis and fermentation (SHF) was applied. However, SHF of SBWO resulted in a specific ethanol yield (222 l-ethanol/t-SB) that was 19\% higher than that of RSWO (186 l-ethanol/t-RS). The specific ethanol yields obtained correspond to 89\% and 87\% of the theoretical yield based on the cellulose content of SB an RS, respectively. The results indicate that alkaline wet oxidation is a promising technology for pretreatment of sugarcane bagasse and rice straw in bioethanol production.

Keywords: bioethanol, SSF, SHF, enzymatic hydrolysis, lignocellulose, biomass waste, inhibition.
Introduction

Recent biotechnological developments have led to an increased focus on utilization of lignocellulosic biomass as a resource for the production of liquid fuels and other chemicals. Multiple biomass substrates have been identified to hold a great potential due to their high content of cellulose and hemicellulose, combined with an abundant annual production (Wiselogel et al., 1996). These include sugarcane bagasse and rice straw (Goel and Ramachandran, 1983), which are the focus of the work presented here.

Sugarcane bagasse is accumulated in large quantities at cane-to-sugar processing plants and consists approximately of 50% cellulose, 25% hemicellulose, and 25% lignin (Pandey et al., 2000). The bagasse produced is traditionally utilized for in-house energy production. Recently, emphasis has been directed at utilization of bagasse in existing bioethanol plants (e.g. in Brazil) for increased ethanol production. Diversification of the production schemes by introducing bagasse as bioethanol substrate has been emphasized as well (Wayman and Parekh, 1990), (Olguin et al., 1995), (Teixeira et al., 2000). In the production of rice significant amounts of rice straw are produced with an approximate composition: Cellulose (40%), hemicellulose (25%), and lignin (15%) (Kadam et al., 2000). The rice straw has traditionally been dried and burned in the fields reducing the local air quality considerably. The increased focus on the emissions during open-field burning have led to legislations in the United States, mandating 75%-100% reductions of open-field burnings (Kadam et al., 2000). This have directed a world wide attention towards utilization of rice straw for production of bioethanol (Moniruzzaman, 1996), (Vlasenko et al., 1997), (Parminder et al., 1998), and (Sulbaran-de-Ferrer et al., 2003).

Lignocellulosic biomass contains sugar components in the form of cellulose and hemicellulose that by various means of pretreatment can be converted into fermentable sugars. Alkaline wet oxidation as pretreatment technology has been identified as promising due high lignin oxidation, high convertibility of cellulose and hemicellulose and a low generation of potential fermentation inhibitors (Bjerre et al., 1996). Enzymatic hydrolysis has been recognized as an attractive and cost effective method for hydrolysis of cellulose and hemicellulose contained in pretreated biomass suspensions (Himmel et al., 1996). However, various factors have been found to affect the enzymatic hydrolysis of the pretreated lignocellulosics – including (a) accessibility and adsorption characteristics of the cellulose, (b) reactivity of the cellulose, and (c) adsorption characteristics of the lignin present (Converse, 1993). These factors are influenced by the biomass composition and the pretreatment method applied (Hsu, 1996). The hydrolysis of cellulose is done by a synergistic activity of three classes of enzymes: Endocellulases, exocellulases, and β-glucosidases (Mansfield et al., 1999). A concern in enzymatic hydrolysis of cellulose is the potential feedback inhibition caused by accumulation of cellubiose and glucose (Himmel et al., 1996).

During ethanol production the enzymatic hydrolysis and glucose fermentation can either be done separately by SHF (separate hydrolysis and fermentation), or at the same time by SSF
(simultaneous saccharification and fermentation). In SHF, optimal conditions to both process steps (i.e. enzymatic hydrolysis and glucose fermentation) are applied. The enzymes liberate sugar monomers in the first step and the fermenting microorganism converts these into ethanol in the second step – with the processes traditionally taking place in separate reactors. Simultaneous hydrolysis and fermentation is done in one reactor with sub-optimal conditions for both the enzymes and the fermenting microorganism. The sugars that are hydrolyzed by the enzymes are immediately converted into ethanol by the fermenting microorganism – keeping the amount of sugar monomers low at all times. The potential benefits of the SSF method have resulted in this method as being the most promising in the conversion of cellulose to glucose (in particular at high substrate and low enzyme concentrations).

The objective of the work presented in this paper was to compare sugarcane bagasse and rice straw as substrates for bioethanol production using alkaline wet oxidation as pretreatment method. The comparison was assessed by enzymatic hydrolysis, SSF, and SHF – evaluating the convertibility of the cellulose contained in the substrates.

**Materials & Methods**

**Biomasses**

Sugarcane bagasse (SB) was obtained from a sugarcane processing plant near Mexico City (Mexico) and rice straw (RS) was collected from the Sacramento Valley (California, USA). The two types of biomass waste were dried in a climate chamber (20 °C and 65% relative humidity), milled to ~5 mm, and stored in plastic bags prior to analysis and pretreatment. The dry matter content (DM) was determined in pre-weighted porcelain crucibles by the weight loss following 24 hours at 105 °C. The composition of SB and RS regarding cellulose, hemicellulose, and lignin were determined by a modified method of Goering and van Soest (1970) and are listed in Table 1. The primary component of the hemicellulose in SB and RS was xylose (90% and 86%, respectively).

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane Bagasse</td>
<td>35%</td>
<td>21%</td>
<td>24%</td>
</tr>
<tr>
<td>Rice Straw</td>
<td>30%</td>
<td>18%</td>
<td>21%</td>
</tr>
</tbody>
</table>

* the numbers do not add up to 100% - the remaining parts are extractives and ash

Both lignocellulosics were pretreated in a specially designed 2 liters loop-type reactor using parameters optimized for alkaline wet oxidation of wheat straw (Schmidt and Thomsen, 1998): 60 g-DM/l, 6.5 Na₂CO₃, 12 bars O₂, 195 °C, and 10 minutes reaction time. After cooling to 35 °C, a fraction of the wet oxidized biomass suspensions were separated in a solid and liquid part to determine the total amounts of cellulose, hemicellulose, and lignin. The composition of the solid fractions were determined as described for the un-treated biomasses,
and the liquid fractions were subjected to weak acid hydrolysis (4 mM H₂SO₄ for 60 min.) prior to HPLC-RID analysis – as described by Bjerre et al. (1996).

<table>
<thead>
<tr>
<th></th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBWO</td>
<td>97%</td>
<td>94%</td>
<td>39%</td>
</tr>
<tr>
<td>RSWO</td>
<td>97%</td>
<td>94%</td>
<td>61%</td>
</tr>
</tbody>
</table>

The recovery of the cellulose and hemicellulose (as xylose) from both types of biomass waste during pretreatment were 97% and 94%, respectively (see Table 2). During alkaline wet oxidation, lignin oxidations were found to be 61% and 39% of what originally was contained in SB and RS, respectively.

**Preparation of inoculum**

Saccharomyces cerevisiae were obtained from a local supplier (Lyngby, Denmark) as compressed baker’s yeast. Cells were taken from the middle of the package and transferred to a 20 ml serum bottle containing basic anaerobic (BA) medium (prepared as described by Ahring et al. (1996) – but at pH 5), supplemented with specific yeast additions and glucose (12 g/l), incubated for 24 hours and plated on standard agarose-gel plates. Single yeast cells were picked from the plates and transferred to glycerol media and stored at –80 °C. The specific yeast additions (YA) were composed of: (all in mg/l) trace metal (EDTA 15.0, ZnSO₄ 7H₂O 4.5, MnCl₂ 2H₂O 1.0, CoCl₂ 6H₂O 0.3, CuSO₄ 5H₂O 0.3, Na₂MoO₄ 2H₂O 0.4, CaCl₂ 2H₂O 4.5, FeSO₄ 7H₂O 3.0, H₃BO₃ 1.0, KI 0.1), vitamins (Biotin 0.050, Ca-pantotenate 25.0, Thiamin-HCL 1.0, Pyridoxine-HCL 1.0, Para-aminobenzoic acid 0.2), and a mixture of ergosterol (6.4) and Tween80 (268.8). Prior to inoculation of fermentation, the yeast cells were grown in BA medium at anaerobic conditions, supplemented with YA, glucose (12 g/l), and transferred twice after 24 hours incubation.

**Enzymatic hydrolysis**

Batch flasks containing wet oxidized biomass suspensions (adjusted to pH 5) were sterilized by addition of tetracycline (40 µg/ml) and supplemented with cellulases (Celluclast 1.5L) and β-glucosidases (Novozym188) at different concentrations. Both enzyme products were kindly sponsored by Novozymes A/S (Bagsværd, Denmark). The enzyme concentrations tested were: 5, 10, 20, 50, and 100 FPU/g-cellulose of Celluclast with supplementation of Novozym188 at 50% (v/v) relative to Celluclast. The batch tests were done as triplicates at 50 °C in a shaking water bath at 150 rpm and samples were taken aseptically at specific times (0, 2, 4, and 7 days). The released glucose and xylose were determined after HPLC-RID analysis (Ahring et al., 1999). The enzymatic hydrolysis of cellulose and xylan are reported as the saccharification – calculated from the total content in the wet oxidized biomass suspensions.
Fermentation experiments

Simultaneous saccharification and fermentation (SSF) experiments were done in 30 ml batch flasks with an active volume of 10 ml. The wet oxidized biomass suspensions (adjusted to pH 5) were distributed in batches, flushed with N\textsubscript{2}/CO\textsubscript{2} (80%/20%), and sealed with butyl rubber stoppers and aluminum crimps. Celluclast 1.5L and Novozym188 were added in the same concentrations as for the enzymatic hydrolysis. Prior to inoculation with \textit{S. cerevisiae} at 10% (v/v), specific yeast additions were added. All batches were incubated at 32 °C with shaking (150 rpm) for 7 days. Samples were taken using sterile and anaerobic techniques (0, 2, 4, and 7 days) and analyzed for glucose, xylose, and ethanol by HPLC-RID (Ahring et al., 1999).

Separate hydrolysis and fermentation (SHF) experiments were done in a 600 ml batch reactor with 250 ml active volume. The batch reactor was connected to a CO\textsubscript{2}-vent, pH control (0.2 M NaOH), and a magnetic stirred. Enzymes (Celluclast: 25 FPU/g-cellulose and Novozym188: 50% (v/v) relative to the Celluclast) and tetracycline (40 µg/ml) were added to the reactor before it was flushed with N\textsubscript{2}/CO\textsubscript{2} (80%/20%) and sealed with a butyl rubber stopper. Samples were taken from a sample port (0, 2, and 4 days) and were analyzed for glucose, xylose, and ethanol by HPLC-RID – as described previously. After 4 days enzymatic hydrolysis the reactor was supplemented with specific yeast addition and inoculated with \textit{S. cerevisiae} at 10% (v/v). Prior to the inoculation, the temperature of the batch reactor was changed to 32 °C. In order to determine the production of ethanol as well as the consumption of glucose and xylose, samples were taken through a sample port (after 0 and 2 days of fermentation) and analyzed by HPLC-RID. Sampling in the SHF test was done using sterile and anaerobic techniques. The batch reactor experiments were performed twice for each of the biomass suspensions and the results are presented as average values of the runs.

Results & Discussion

In evaluating the potential of using alkaline wet oxidation as pre-treatment methods for sugarcane bagasse and rice straw, enzymatic convertibility of the cellulose fraction of the pretreated biomass suspensions were explored. Production ethanol using simultaneous saccharification and fermentation (SFF) of the wet oxidized sugarcane bagasse (SBWO) and rice straw (RSWO) was assessed at the same enzyme concentration as used in the enzymatic hydrolysis, Furthermore, the ethanol production from two types of biomass suspensions were compared by separate hydrolysis and fermentation (SHF).

Enzymatic hydrolysis

During enzymatic hydrolysis of pretreated sugarcane bagasse and rice straw both glucose and xylose was released as monomeric sugars. The release of glucose from the wet oxidized sugarcane bagasse (SBWO) and rice straw (RSWO) are depicted in Fig. 1 and Fig. 2, respectively.
Comparing the levels of glucose released during 7 days of enzymatic hydrolysis reveals that SBWO liberate higher amounts of glucose compared to RSWO. This can be explained by the higher content of cellulose in the SB – see Table 1. It was evident that the release of glucose during enzymatic hydrolysis of SBWO and RSWO increased with increasing enzyme concentrations. This correlation of increased hydrolysis at higher enzyme concentrations was not surprising as the relation have been reported in several studies with pretreated sugarcane.
bagasse and rice straw (Azzam, 1987), (Szczodrak, 1988), (Vlasenko et al., 1997), (Parminder et al., 1998), and (Alfani et al., 2000).

However, the increase in glucose concentration proportional to the enzyme concentration was quite different for the two kinds of biomass suspensions. No significant increase in the saccharification of RSWO was found above 10 FPU/g-cellulose after 4 days hydrolysis (Fig. 2) whereas an increased glucose release from SBWO was seen for concentrations up to 50 FPU/g-cellulose. The amount of cellulose relative to enzyme can be speculated to control the level at which the maximum glucose release was found. Zheng and Matsumoto (1998) tested the effect of increased enzyme concentration using a constant substrate concentration of sugarcane bagasse (50 g/l), and found no increase in the saccharification from 1.2-10 mg-enzyme/ml. The researchers argued that when the amount of enzyme adsorbed to the cellulose fraction was at a maximum, no additional effect by enzyme supplementation was seen. This fact indicates that the level of enzyme-to-cellulose saturation was controlled by the enzyme-to-cellulose adsorption, which corresponds with the observations found in the present study.

Even at high enzyme loadings (100 FPU/g-cellulose) incomplete hydrolysis was evident for SBWO and RSWO with maximum yields of 72% and 67% of theoretical, respectively. The significantly reduced saccharification of the biomass suspensions suggests that dissolved components reduce the ability of the enzymes to adsorb and completely hydrolyze the cellulose. Incomplete hydrolysis – when testing enzymatic hydrolysis in unwashed biomass suspensions – has been reported by Tengborg et al. (2001) who found 52% saccharification of an unwashed whole slurry of steam exploded (STEX) spruce at 120 FPU/g-cellulose (120 hours). In general, a higher degree of saccharification was found for SBWO compared to RSWO (Fig. 1 and Fig. 2). The higher saccharification of SBWO indicates that a larger fraction of the cellulose was accessible to the enzymes compared to RSWO. As cellulases have been found to adsorb to lignin components (Ooshima et al., 1990), the higher enzymatic convertibility observed for SBWO can be speculated to relate to the lower lignin content of SBWO compared to the RSWO – see Table 2. Sewalt et al. (1997) also studied the inhibitory effect of lignin up to 15% and found significant reductions (60%) of the cellulose hydrolysis at the highest lignin concentration.
The levels of saccharification of SBWO and RSWO found in the present study were coherent with results obtained by other research groups using various pretreatment methods – see Table 3.

Table 3 – Summary of work done on enzymatic hydrolysis of pretreated sugarcane bagasse and rice straw. WO: wet oxidation, STEX: steam explosion, AFEX: ammonia freeze explosion

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Pretreatment method</th>
<th>Enzyme Loading (FPU/g-cellulose)</th>
<th>Saccharification</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB</td>
<td>WO</td>
<td>5 - 100</td>
<td>43% - 72%</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>STEX</td>
<td>25</td>
<td>41% - 67%</td>
<td>(Kaar et al., 1998)</td>
</tr>
<tr>
<td></td>
<td>STEX*</td>
<td>13</td>
<td>83%</td>
<td>(Morjanoff and Gray, 1987)</td>
</tr>
<tr>
<td>RS</td>
<td>WO</td>
<td>5 - 100</td>
<td>46% - 67%</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>AFEX</td>
<td>18</td>
<td>32%</td>
<td>(Vlasenko et al., 1997)</td>
</tr>
<tr>
<td></td>
<td>AFEX</td>
<td>15</td>
<td>55%</td>
<td>(Sulbaran-de-Ferrer et al., 2003)</td>
</tr>
<tr>
<td></td>
<td>Alkali-steam</td>
<td>25</td>
<td>54%</td>
<td>(Parminder et al., 1998)</td>
</tr>
<tr>
<td></td>
<td>STEX</td>
<td>18</td>
<td>46%</td>
<td>(Vlasenko et al., 1997)</td>
</tr>
<tr>
<td></td>
<td>Acid-steam</td>
<td>18</td>
<td>60%</td>
<td>(Vlasenko et al., 1997)</td>
</tr>
</tbody>
</table>

* enzymatic hydrolysis of fractionated biomass suspension

The similar levels of enzymatic hydrolysis clearly indicate that alkaline wet oxidation is a promising pretreatment technology to enhance the enzymatic hydrolysis of sugarcane bagasse and rice straw for bioethanol production.

**Simultaneous saccharification and fermentation**

The results obtained from the SSF of both biomass suspensions indicate that pretreatment using alkaline wet oxidation is a potential method for SB and RS as high ethanol yields at low enzyme concentrations were found – see Table 4.

The maximum ethanol yields after 7 days SSF of SBWO and RSWO were 0.39 g/g-glucose and 0.31 g/g-glucose, respectively. These yields correspond to 76% and 62% of the theoretical yields of the SBWO and RSWO, respectively, based on the content of cellulose. Insignificant increases of the ethanol yields from SSF of RSWO was found when the enzyme loading was increased from 10 FPU/g-cellulose to 100 FPU/g-cellulose as well as when the fermentation time was increased from 4 to 7 days. The effect of higher enzyme loadings and longer fermentation time was found to be more significant when SBWO was treated by SSF. This implies that the level of enzyme-to-cellulose saturation seems to be related to the nature of the biomass. Eklund and Zacchi (1995) found no significant increase in the ethanol yield during SSF of STEX willow above 18 FPU/g-DM, whereas van Walsum et al. (1996) found increasing ethanol yields in SSF of liquid hot water (LHW) treated bagasse from 7-30 FPU/g-cellulose. This is coherent to the different levels of ethanol yield following SSF found in the present study.
<table>
<thead>
<tr>
<th>Enzyme concentration (FPU/g-cellulose)</th>
<th>Time (d)</th>
<th>SBWO</th>
<th>RSWO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ethanol Yield (g/g)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Ethanol Yield (%)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.04</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.14</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.21</td>
<td>41%</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0.08</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.23</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.27</td>
<td>54%</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.12</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.30</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.34</td>
<td>67%</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>0.15</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.34</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.38</td>
<td>74%</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>0.10</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.36</td>
<td>69%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.39</td>
<td>76%</td>
</tr>
</tbody>
</table>

<sup>a</sup> as g-ethanol/g-glucose in the wet oxidized biomass suspensions  
<sup>b</sup> relative to the cellulose contained in the wet oxidized biomass suspensions

The ethanol yields from SSF of pretreated sugarcane bagasse found in the present study were comparable to the SSF results reported by van Walsum et al. (1996). LHW pretreatment at 80 g/l resulted in approximately 60% ethanol yield (of theoretical) at 15 FPU/g-cellulose during 7 days fermentation using *T. reesei* cellulases supplemented with Novozym188 and *S. cerevisiae* D5A.

**Comparing enzyme hydrolysis and SSF**

A clear correlation between the degree of saccharification and the ethanol yield (SSF) was found indicating that feed-back inhibition was not the governing factor during the enzymatic hydrolysis of SBWO and RSWO. It can be speculated that the results obtained was influenced by the low substrate concentration (~20 g-cellulose/l) used in this study compared to previous studies (Philippidis et al., 1993) (Ramos et al. (1993)) that showed increased enzymatic convertibility by application of SSF – due to reduced feed-back inhibition of the enzymes.

In contrast to the enzymatic hydrolysis, the fermentation of SBWO resulted in significantly lower ethanol yields compared to what could be expected from the saccharification during the initial period (2 days of incubation). It can be speculated that the initial enzymatic hydrolysis was reduced due the lower temperature applied during SSF compared to the enzymatic hydrolysis (50 °C vs. 32°C). At 30 °C, the activity of *Trichoderma* cellulases (of which
Celluclast belongs) can be reduced to 50% relative to its optimum temperature (Huang and Chen, 1988), (Grohmann, 1993). This is in agreement with the comparison of the results obtained during enzymatic hydrolysis and SSF (Table 3 and Table 4).

Apparently the cellulose fraction available in RSWO was more reactive than in SBWO as it was found that RSWO yielded higher saccharification, faster initial hydrolysis, and higher ethanol yields at low enzyme loadings – see Table 4. This corresponds to the results reported by Goel and Ramachandran (1983) who found an enzymatic hydrolysis of 80% for pretreated rice straw compared to 65% for pretreated sugarcane bagasse within the first 8 hours of hydrolysis. The enzymatic hydrolysis was tested at a low enzyme concentration (1 IU/ml) using alkaline pretreatment.

**Separate hydrolysis and fermentation**

The reactor fermentations at SHF mode using pH-control are presented in Fig. 3.

As can be seen the glucose released during the enzymatic hydrolysis was completely fermented by *S. cerevisiae* into ethanol. It was evident that the released glucose and the production of ethanol were higher using SBWO as biomass substrate in SHF. After 4 days enzymatic hydrolysis at 25 FPU/g-cellulose, the saccharification of SBWO and RSWO was found to be 87% and 72%, respectively. However, similar ethanol yields were found after 2 days fermentation of SBWO and RSWO with *S. cerevisiae*. It can be speculated that the
cellulose contained in the RSWO was being hydrolyzed during fermentation at a higher level than cellulose in SBWO. The specific ethanol yield of sugarcane bagasse (222 l-ethanol/t-SB) was found to be 19% higher than that of rice straw (186 l-ethanol/t-RS). These yields correspond to 89% and 87% of the theoretical yield based on the cellulose content of the untreated sugarcane bagasse and rice straw listed in Table 1.

**Conclusion**

Alkaline wet oxidation was assessed as pretreatment method prior to enzymatic hydrolysis and glucose fermentation of sugarcane bagasse (SB) and rice straw (RS). Incomplete hydrolysis was found in both wet oxidized sugarcane bagasse (SBWO) and rice straw (RSWO) with maximum saccharification of cellulose at 73% and 62%, respectively. As no significant increase in the ethanol yields (relative to what could be expected from the enzymatic hydrolysis) was seen during SSF, feed-back inhibition of the enzymes was concluded not to be present. Based on the higher yields and the lower lignin content of SBWO, it was speculated that the availability of cellulose was higher in SBWO compared to RSWO. Separate hydrolysis and fermentation of SBWO and RSWO at 25 FPU/g-cellulose resulted in comparable ethanol yields, however, the ethanol potential of SBWO was found to be approximately 20% higher than RSWO. The specific ethanol potential of SB and RS following SHF was 222 l-ethanol/t-DM and 186 l-ethanol/t-DM, respectively. The results emphasize the capability of using alkaline wet oxidation for pretreatment of various types of lignocellulosic biomass waste.

**Acknowledgements**

The financial support from Council of Development Research (RUF) within DANIDA was greatly acknowledges (project number 91097). The assistance of Anne Belinda Thomsen, Helene Klinke and Tomas Fernqvist (Risoe National Laboratories) and Gitte Hinz-Berg (EMB-DTU) was greatly appreciated.

**References**


Session 7 – Energy Savings and Efficiency Improvements

Chairman: Jørgen Henningsen, Weatherhead Centre for International Affairs, Cambridge, USA
EurEnDel - Technology and Social Visions for Europe’s Energy Future - a Europe-wide Delphi Study

Birte Holst Joergensen, & Poul Erik Morthorst, Risoe National Laboratory, Denmark
Anna Oniszk-Poplawksa & Lukasz Jaworski, EC Baltic Renewable Energy Centre, Poland
Augusto Ninni, Oliviero Bernardini and Monica Bonacina, IEFE-Università Bocconi, Italy
Daniela Velte, Juan Pedro Lopez Araguas & Oliver Nielsen, Prospektiker, Spain
Timon Wehnert & Wolfram Joerss, IZT, Germany

Abstract

The paper reports on the results from the EURENDEL project supported by the EU Fifth Framework Programme. EurEnDel is the first Europe-wide Delphi survey on the energy sector. With a time horizon of 2030 it provides information on long-term developments of energy technologies. In addition to this technology-push perspective, a normative, social-pull perspective has been included in order to identify demands on the future energy system. The paper concludes with research policy recommendations, which derive from the comparison of the technological trends with the societal demands.

1.1 Background

Availability of energy is a prerequisite for economic growth and welfare in Europe and elsewhere. Nowadays, we are totally dependent on an abundant and uninterrupted supply of energy for living and working. All over the world, increasing energy consumption, liberalisation of energy markets and the need to take action on climate change are producing new challenges for the energy sector. At the same time there is increasing pressure for research, new technologies and industrial products to be socially acceptable and to generate economic wealth and quality of life. The result is a complex and dynamic set of conditions affecting decisions on investment in research and new energy technology (Larsen, 2002).

Therefore, better and more robust decision making in R&D research is needed. EurEnDel aims at providing advice on energy R&D priorities, based on sound expert knowledge. Equal emphasis is placed on the technology push perspective “What will the future be like?” and the normative perspective “What should the future be like?”. In a world of uncertainties, EurEnDel adapts the classical, iterative and expert-based Delphi judgement, employing a variety of foresight approaches both in the design of the questionnaire and in the later analysis of the results (for more information see www.eurendel.net).

More than 3,400 energy experts from 48 countries were invited to participate in this two-round, web-based Delphi survey. The response rate of about 20%, obtained in the first round, ensures that the results represent a broad European perspective on the challenges that Europe’s energy system will be facing.

1.2 Main survey Results

The Delphi results and the experts’ comments indicate that there is no business-as-usual
case for the European energy system, when looking at a longer-term horizon (2030). Major structural changes are already taking place and are likely to intensify in the coming decades. The large majority of the respondents are nevertheless optimistic about the potential for technological progress in the field of energy.

A comparison of the EurEnDel Delphi results with two energy scenarios, which were developed from quantitative models\(^1\), indicates that the EurEnDel participants anticipate more rapid development of substitute technologies and higher market shares, particularly those based on renewable energy resources. Recent research suggests that economic models tend to underestimate the potential of emerging technologies (Laitner 2004). Therefore, the EurEnDel results on expected time frames should be more correctly interpreted as identifying achievable future developments, given the right framework conditions and incentives.

**Technology Trends**

The 19 technology statements highlighted important developments in energy demand and supply, focussing on emerging technologies most relevant for formulating R&D recommendations. The selection does not imply that excluded technologies are not significant for future energy systems.

**Time of Occurrence**

The technology statements involved varying degrees of accuracy ranging from specific penetration rates, such as 25% market share, to less precise indications distinguishing between Practical Use (the first practical use of an innovative product or service) and Widespread Use (the product or service is in common use).

Graph 1 presents the anticipated Time of Occurrence as assessed by the experts in the second round of the Delphi survey, who considered themselves to be either experts, knowledgeable or at least familiar with the topic. As indicated by the mean value of the returns, most technologies addressed in the survey were expected to experience major advances in the medium-long term (2020 – 2030). The right hand side of Graph 1 reports the share of respondents, who found the corresponding statement unlikely ever to occur. The statistical spread of answers became smaller from the first to the second round, as intended with the Delphi method (Loveridge et al., 1995; Linstone & Turoff, 1974).

\(^1\) These were “European Energy and Transport - Trends to 2030” published by the European Commission, DG TREN (Mantzos et al. 2003) and the “With Climate Policies” (WCLP) scenario which is used as one of the baseline scenarios in the EU-wide CAFE (Clean Air For Europe) process managed by the European Commission, DG Environment (Zeka-Paschou 2003).
### Important findings by technology domain:

- **Energy Demand.** There was broad consensus on the energy demand topics. Doubling the energy efficiency in industrial production was considered to be likely before 2030 by 65% of the respondents and 75% of the respondents anticipated 50% of all new buildings in Europe to be low energy buildings before 2030.

- **Transport.** A 20% market share of fuel cell driven cars was expected by the experts in the late 2020s. Note that this is well before hydrogen is expected to play a significant role in Europe’s energy system. On the issue of a 25% share of biofuels for transportation, the expert’s opinions were divided: The majority expected this to happen before 2030, but 15% of the respondents considered 25% a too larger number due to the limited overall potential for biomass production.
• **Storage, Distribution and Grids.** There was consensus that the trend towards a more decentralised electricity supply prevailed. A 30% share of decentralised generation was expected by 2020. In contrast there was quite a controversy when and if at all large international grids allowed for an energy transportation of regionally produced renewable energy. Energy storage was considered to be in widespread use by the early 2020s to support renewable energy systems. Hydrogen, as one storage option was considered to constitute a significant part only after 2030.

• **Energy Supply.** The experts were divided concerning the future of nuclear energy. Both fusion and fission received the highest “never” shares. The experts that considered these technologies to come anticipated passive safe reactor types around 2025. Plasma confinement technologies, a prerequisite for fusion reactors, were not considered to be in practical use before 2040. As for renewable energy sources there was little doubt that a 25% share of Europe’s total energy supply would be possible. 66% of the respondents considered it likely that this share was reached before 2030. A high contribution of photovoltaic to this share was a long-term goal. The majority of respondents considered a 5% contribution of PV to Europe’s electricity supply realistic only after 2030.

**Impact Assessment**

The experts were asked to rate the anticipated impact of the technology statements in the areas of Wealth Creation, Environment, Quality of Life and Security of Supply. An index based calculation of the impacts, allowed comparison between the technology statements (see Graph 2). Major findings were:

- A share of 25% renewables for Europe’s total energy supply was considered to be the most beneficial. In addition to the positive ecological impact, the strong contribution to security of supply was stressed.
- Following closely was efficient use of energy comprising novel production processes and low-energy buildings.
- Nuclear energy (safe passive reactors and plasma confinement technologies for nuclear fusion) received low overall ratings. The greatest positive contribution of these technologies was seen in the area of security of supply.
- CO₂ capture and sequestration in fossil fuel plants was assessed to be beneficial only for environmental reasons, but generally obtained very low ratings.
- Fuel cells and hydrogen were generally perceived as providing only medium benefits. However, hydrogen production from renewable sources was judged to have more positive impacts than hydrogen produced from diverse sources.
Graph 2: Average ratings of Delphi statements for the four areas of impact.

Most technology statements scored higher on environment and on security of supply rather than on wealth creation and quality of life.

Supportive Actions

Experts were asked to assess which actions were necessary to promote an earlier occurrence of the statements. The results of this assessment were an important contribution in the formulation of policy recommendations.

An overview of the results is presented in Graph 3, displaying the kind of actions that were considered most important to enhance higher market penetration rates for the respective technologies.

Graph 3 also draws attention to those technologies which may be considered as a “safe-bet”, in the sense that all analyses carried out within the project resulted in their priority ranking, including their beneficial impacts and their contributions to meet social demands.
<table>
<thead>
<tr>
<th>“Safe-</th>
<th>Basic R&amp;D</th>
<th>Applied R&amp;D</th>
<th>Fiscal</th>
<th>Regulations</th>
<th>Public</th>
<th>When will it happen</th>
</tr>
</thead>
<tbody>
<tr>
<td>bet”</td>
<td></td>
<td></td>
<td>measures</td>
<td></td>
<td></td>
<td>happen</td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Biomass for heating widely used</td>
<td></td>
<td></td>
<td></td>
<td>Mid term 2011-2020</td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>15% freight on rail</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Novel and more efficient processes in industry (50% of demand reduction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Reduction of energy demand in the housing sector (intelligent systems 50% of buildings)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>25% of RES in primary energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Ocean technologies in practical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>30% of distributed energy generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>20% of fuel cells for transport</td>
<td></td>
<td></td>
<td></td>
<td>Long term 2021-2030</td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>25% of biofuels for transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Energy storage for intermittent RES widely used</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Passive safe reactors (nuclear fission) in practical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Superconductive materials are widely used in power systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>CO₂ capture and sequestration in practical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Practical use of international grids for RES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>5% of Photovoltaics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Nuclear fusion in practical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>High market penetration of H₂ from RES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>High market penetration of H₂ from diverse sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>★</td>
<td></td>
<td>Biological production of H₂ in practical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graph 3: Summary of Actions Needed**

**Three Social Visions**

The experts were asked to assess the importance of energy technologies and sources on the background of the set of values identified in three social visions:

- The vision of Individual Choice placed emphasis on individual needs, liberalised markets and consumer sovereignty in the choice of products and services.

- The vision of Ecological Balance valued protection of the ecosystem, ecological awareness and sustainable production and consumption.

- The main features of the vision of Social Equity were a reduction of income disparities and of social exclusion, accompanied by community balance and cohesion at the European level, while allowing for regional solutions.

The most significant conclusions emerging from the survey responses were:

- Energy conservation technologies and demand-side management techniques were considered to be of highest importance and reached the highest ranking in
each of the three visions.

- In Individual Choice, fuel cells were given very high importance, presumably as an option to develop individually tailored energy solutions.
- In Ecological Balance, wind and biomass were rated second, seemingly reflecting their perceived limited impact on environment.
- In Social Equity, biomass was rated highly probably because of its high labour intensity and potential for regional wealth creation.
- The role of hydrogen was considered to be rather independent of social values and achieved intermediate ratings in all three visions.
- CO₂ sequestration received a low rating, except for Environmental Balance, in which it was assigned intermediate importance.
- Nuclear fission was rated lowest in importance in all three visions.

1.3 Conclusions

Summarised below are the most important results of the EurEnDel survey. Since the assessment of long-term trends and needs in the fields of energy technologies was the core objective of EurEnDel, a special emphasis is put on recommendations towards R&D policy which are in line with the trends and needs identified in the survey.

**Highest Priority: Energy efficiency**

According to EurEnDel results energy efficiency technologies are due to become the most determining element for Europe’s energy future. The experts are clear cut in their assessment that technologies to reduce energy demand are most beneficial in their impacts and have to be favoured independently of the societal vision pursued. However, the analysis shows a high underinvestment risk in energy efficiency measures. Therefore supportive actions should be intensified combining research, fiscal incentives and the improvement of acceptability by end-users.

Improving the energy efficiency in housing and industry needs strong backing through applied research. Long-term strategies are vital since high rates of energy reduction per GDP unit can be achieved only in long term perspective, after 2020. Therefore, promotion of R&D should be complemented by fiscal incentives and regulation.

Hampering the rising energy demand in the transportation sector was identified as a crucial challenge for Europe’s energy system. However, the analysis shows no simple solution, which is apt to meet this challenge. Thus, efforts should be intensified on various levels to employ all available means.

Fuel cells seem to be a safe-bet to play a major role in the future energy system, contributing to more energy efficiency in transportation and bring down local emissions. Fuel cell driven cars are predicted to have a major market share already before the hydrogen economy is established. Thus flexibility of design with the option to use natural gas as a transition fuel will be crucial in the development path of fuel cells for transportation.

Fuel cells for transport and hydrogen production already now need application of market instruments (mainly fiscal measures), and not only research support. The economy of scale should lead to significant cost reduction.
If there is a political will to increase freight transportation by railways, the instruments to support it must change. The most crucial should be instruments typical for already mature technologies, i.e. fiscal and regulatory measures.

High Potential: Renewables

The majority of the experts believe that 25% of Europe’s total energy demand can be covered by renewable energy sources before 2030. However, this target is only realistic in combination with higher energy efficiency and if renewable energy technologies receive appropriate support.

Experts expressed the opinion that the development of renewables can be impeded due to a competition from other emerging technologies, especially natural gas used as a fuel for fuel cells and hydrogen production. Also application of CO$_2$ sequestration can improve the environmental performance of fossil fuels and thus slow down the development of renewables.

Biomass has a high potential to play a significant role in Europe’s energy future. Experts highlight positive impacts of widespread use of biomass not only for ecologic reasons, but also as a means to create local income in rural areas.

For biomass and biofuels technologies applied research should be promoted to tap the potential of this energy source on a short to medium time frame. However, biomass resources are limited and there will be a competition for the use of land for biomass production for different purposes. High uncertainties exist concerning the exact role of biofuels in Europe’s future energy system further. The analysis of the support schemes on the EU level has shown that biofuels require promotion measures. This, however, was not confirmed by the experts. It seems that biofuels are accepted but the lack of comfort of use still requires more applied research to eliminate inconveniences. Also in order to use biofuels a proper fiscal policy is necessary to increase its competitiveness.

Photovoltaic has a potential to play a significant role in Europe’s energy future in the long term. A contribution of 5% to Europe’s electricity supply (which would basically imply that the technology is economically competitive) is anticipated between 2030 and 2040. Favourable framework conditions are necessary for this ambitious target. The key element being applied research, but also long-term support through basic research and economic incentives are necessary.

Not only technical and economical barriers but also public acceptance are one of the key impeding factors in case of some renewables (e.g. wind or biomass), such as land change issues, landscape pollution, smaller comfort of use as well as reluctance to unknown technology.

Increasing Importance: Distributed electricity generation and energy storage

Energy storage is not a mere element but one of the key stimuli inevitable for the further development of renewables characterised with intermittent electricity production. Energy storage is in the risk of underinvestment so special attention should be paid to appropriate levels of support for both basic and applied research.

Energy storage technologies will become increasingly important in the future. Hydrogen is one storage option, but due to the anticipated long time horizon until hydrogen can contribute with a significant part to Europe’s energy system other storage alternatives have to be also followed (batteries, flywheels, super caps etc.).
The experts point out that for any assessment of hydrogen related technologies it is vital to consider where the hydrogen comes from. In their opinion a hydrogen production purely from renewable sources is to be preferred mainly for environmental reason. The goal of renewable hydrogen production should be implemented, but other sources (natural gas, coal or nuclear) may serve as bridging solutions in a transitional period.

Superconductive materials were considered as a technology, which supports fulfillment of the main policy and technology goals such as strengthening of the European electricity transmission grid, reduction of the energy demand and more efficient energy storage. Although it is now a very immature technology 98% of the experts think that it is a viable option for the future energy system.

**Controversial Issues: Nuclear energy**

The introduction of passive safe reactor types in Europe was anticipated by the large majority of the experts after 2020. However, it is a quite controversial issue where 20% of the experts do not believe in this development. In the impact assessment nuclear fission was given very low ratings despite of their important input to security of power supply.

Roughly three quarters of the experts believe that at some point in the future nuclear fusion will be in practical use. However it was the most controversial issue covered in the survey. Due to the very long-term perspective for its technological break-through fusion generally received very low impact ratings. The perception of nuclear fusion should be decoupled from the perception of nuclear fission in the public mind, according to experts.

**Intermediate Solution: Natural Gas**

Natural gas can play an important role towards a more sustainable energy supply of Europe, however, the experts warn to rely excessively on this energy source for security of supply reasons. Many emphasize the transitional character of this energy source as a bridge to a more sustainable energy future not based on fossil fuels. A strong increase in natural gas imports can be anticipated together with high investments needed to build up the necessary infrastructure (pipelines and liquefaction facilities). R&D efforts in this field can contribute to bring down costs of natural gas transportation and storage infrastructure.

**Other issues**

Solving problems with safety and long-term reliability is the most crucial for the development of nuclear power, hydrogen production and storage as well as CO\textsubscript{2} capture and sequestration.

The level of energy prices should reflect the external costs, in order to increase economic competitiveness of emerging technologies (both demand and supply side technologies) more competitive on the energy market.

**1.4 References**


Session 8 – Fuel Cells

Chairman: H. J. Neef, Forschungszentrum Jülich, Germany
Advances in Solid Oxide Fuel Cell Technology (SOFC) at Siemens Westinghouse

Shailesh D. Vora
Siemens Westinghouse Power Corporation

Abstract

Siemens Westinghouse is the recognized leader in the development of SOFC technology and has developed materials and processes that have produced robust and reliable SOFCs. Siemens Westinghouse seal-less SOFCs have demonstrated long life, ability to thermal cycle, and no noticeable performance degradation over several years of operation.

Until recently, Siemens Westinghouse’s primary interest has been developing SOFCs for large power generation systems, and the key to achieving acceptable cost was in developing the largest practical size cell. However, high system cost ($/kWe) still remains a major barrier to commercialization. Cost reduction programs in the areas of cell, module and BOP components are under continuous development. The focus of this paper will be advancements in the cell area through development of new materials and lower cost fabrication processes applicable to mass production.

Siemens Westinghouse is also focused on enhancing cell performance to increase the rating of SOFC systems with the same number of cells, thereby reducing system cost. Siemens Westinghouse is developing ways to increase the power output of the cells by advancements in materials, processing and cell geometry. Notable among these is the development of a new cell design that utilizes the seal-less feature but reduces the current path length. This new design referred to as high power density (HPD) cell has a closed end similar to the tubular design, but has integral ribs that act as bridges for current flow, reducing the current path relative to the tubular design. The shorter current path results in lower cell resistance, and hence higher power output than tubular cells. A cost benefit can also be realized by the elimination of full-length air feed tube, since the ribs form inlet and exhaust air channels.

The status and prospect of cell cost reduction and power enhancement programs will be reviewed.

1 Introduction

Siemens Westinghouse is the recognized leader in the development of SOFC technology and has developed materials and processes that have produced robust and reliable SOFCs. Siemens Westinghouse seal-less SOFCs have demonstrated long life, ability to thermal cycle and no noticeable performance degradation over several years of operation.

Siemens Westinghouse’s primary interest has been developing SOFCs for stationary power generation systems, and the key to achieving acceptable cost was in developing the largest practical size cell. However, high system cost ($/kWe) still remains a major barrier to commercialization. In addition to cost reduction programs for cell, module and
Balance of Plant (BOP) components, Siemens Westinghouse is focused on enhancing cell performance to increase the power output of SOFC systems with the same number of cells, thereby reducing system cost. Another approach being explored to lower cost is to lower the system operating temperature allowing the use of lower purity module insulation materials.

This paper will focus on strategies employed in enhancing cell power, fabrication of cells and generator to prove the concepts.

2 Cell Power Enhancement

Siemens Westinghouse is developing ways to increase the power output of the cells by advancements in materials, processing and cell geometry. The approach used to enhance cell power is to reduce the two dominant voltage loss mechanisms viz cathode polarization and ohmic resistance, as shown in Figure 1. For Siemens Westinghouse cathode supported tubular cells, cathodic activation polarization is the most dominant voltage loss mechanism accounting for approximately 60% of voltage loss at 950°C. It is even higher at lower operating temperatures. Good performance over a wider operating range (800 –1000°C) is desired due to the temperature gradients that exist in a SOFC generator that nominally operates at 1000°C. Cathodic concentration (or pore) polarization also plays a secondary role in lowering cell performance.

![Figure 1. Cell Power Enhancement Program](image)

2.1 Cathode Polarization

The use of a porous, mixed electronic and ionic conducting interlayer between the cathode and the electrolyte has been proposed to reduce the activation polarization at the cathode. Typically, this interlayer consists of one phase, termed the “electrocatalyst” which is predominantly an electronic conductor, a second phase which is predominantly an ionic conductor and porosity which provides the critical third phase for the oxygen reduction (charge transfer) reaction. It is critical to have sufficient porosity in this interlayer to provide abundant triple phase boundaries which serve as reaction sites for oxygen reduction. Incorporation of this interlayer extends the electrochemically active triple phase boundaries from the cathode/electrolyte interface into the cathode.
The state-of-the-art Siemens Westinghouse cathode supported tubular SOFCs utilize a thin (~1μm) interlayer of cerium oxide between the cathode and the electrolyte. The purpose of applying the cerium oxide layer is to minimize the formation of insulating phases (e.g. lanthanum zirconate) by chemical reaction between the cathode and the electrolyte at processing temperatures. In addition, the cerium oxide interlayer also provides a beneficial effect of increased electrochemical reaction area due to the mixed electronic and ionic conductivity of cerium oxide. However, the effectiveness of cerium oxide as a retardant for chemical reaction between the cathode and the electrolyte is relatively poor, especially at higher processing temperatures. Furthermore, at operating temperatures between 800 - 1000°C, cerium oxide is neither a preferred electronic conductor nor a preferred ionic conductor. To overcome the limitations of cerium oxide, a composite interlayer consisting of doped lanthanum manganite (electrocatalyst) and yttria-stabilized zirconia (ionic conductor) was used at the cathode-electrolyte interface.

The processing steps for various cell components were as follows: cathode – extrusion followed by sintering, interlayer – slurry deposition, interconnection – plasma spraying, electrolyte – plasma spraying followed by a high temperature sintering step, anode – plasma spraying. These cells were then electrically tested at 85% fuel utilization. Voltage versus current density measurements were made at 900°C to compare the cell performance with different cathode-electrolyte interlayers. Figure 2 shows comparison of cell voltage versus current density for cells with a cerium oxide interlayer and a composite interlayer. At a constant cell voltage of 0.65 volt, the cell with composite interlayer has approximately 30% improved performance relative to the cell with cerium oxide interlayer. The power enhancement was attributed to lowered activation polarization due to increased reaction sites for the composite interlayer.

To reduce the cathode concentration polarization, it is essential to maintain adequate porosity in the cathode. Exposure to high temperatures during cell processing steps have a tendency to reduce the porosity in the cathode, thereby contributing to increased cathodic concentration polarization. Thus, to reduce concentration polarization, the electrolyte plasma spray process was modified such that a lower post plasma spray sintering temperature was required to achieve required gas tightness in the cell.

![Figure 2. Voltage versus Current Density Plots for Tubular Cells with Cerium Oxide Interlayer and a Composite Interlayer](image-url)
Once again, two cathode supported tubular cells, one with a cerium oxide interlayer and another with a composite interlayer (50% doped lanthanum manganite + 50% yttria stabilized zirconia) were fabricated. This time, for the cell with the composite interlayer, the electrolyte sintering temperature was lowered. Thus the cell with the composite interlayer addressed both activation and concentration cathodic polarizations. Figure 3 shows comparison of cell voltage versus current density for these cells. At a constant cell voltage of 0.65 volt, the cell with composite interlayer and lower temperature sintered electrolyte has approximately 50% improved performance relative to the cell with cerium oxide interlayer. No performance degradation was observed after 1000 hours of testing. The power enhancement was attributed to lowered cathodic polarization. The increased power at lower operating temperature is particularly noteworthy because, as stated earlier, temperature distribution ranging from 800-1000°C can exist in a SOFC generator that nominally operates at 1000°C. The performance improvement attributable to lowered cathode polarization at 1000°C is estimated at 30% and 70% at 800°C.

Figure 3. Voltage versus Current Density Plots for Tubular Cells with Cerium Oxide Interlayer and Low Temperature sintered electrolyte and Composite Interlayer

2.2 Ohmic Resistance

The ohmic losses are a function of resistivities of cell materials and the current path length. For Siemens Westinghouse cathode supported tubular cells, even though the electrolyte resistivity is several orders of magnitude higher than the cathode and the anode, due to its lower thickness (∼ 40 µm), it does not contribute significantly towards ohmic loss. Longer current path length, due to relatively large diameter tubular geometry, is a dominant ohmic loss mechanism. To address the ohmic losses, a new cell design that combined the seal-less feature and a flattened cathode tube with integral ribs has been under development. This new design, referred to as high power density (HPD) cell, has a closed end similar to the tubular design. The ribs reduce the current path length by acting as bridges for current flow. This cell design, due to shorter current path has relatively lower ohmic resistance than the present tubular cells. Figure 4 shows the tubular and the HPD cell designs. Analytical modeling is ongoing to optimize the number of ribs for maximum power and mechanical stability against thermal stresses during operation. Based on initial results, HPD cells with five channels (HPD5) were selected for cell preparation, develop manufacturing processes and test electrical performance. Also, HPD cells with 10 channels (HPD10) were selected to explore the upper bounds of cell production.
Figure 4. High Power Density (HPD) Cathode Supported Seal-less Planar Concept.

To determine the performance enhancement due to HPD cells, 75 cm active length HPD5 and HPD 10 cells were fabricated using the steps described above for tubular cells. Both types of HPD cells had composite interlayers applied at the cathode-electrolyte interface to reduce cathode activation polarization.

Figure 5 shows comparison of cell voltage versus current density for a tubular cell with cerium oxide interlayer and HPD5 and HPD10 cells with composite interlayers. The tests were carried out at 900°C and 85% fuel utilization. At a constant cell voltage of 0.65 volt, HPD10 cell has approximately 75% improved performance relative to the tubular cell. No performance degradation was observed after 1000 hours of testing of HPD10 cell as shown in Figure 6. Figure 7 shows the voltage-time plot of HPD5 cell, which was tested for over 3000 hours at 1000°C. In the case of HPD cells, the power enhancement was attributed to reduced current path length in the HPD cells and reduced cathode polarization. Further power enhancement can be obtained by optimizing the HPD cell design for number of ribs and incorporating processing improvements and increasing cathode conductivity as described in Figure 1.

Figure 5. HPD Cell Testing.
2.3 HPD Cell Bundling

HPD5 cells were connected using nickel felts in a 6 cell bundle to test HPD cells in a generator environment. Figure 8 shows a HPD5 cell bundle. A proof-of-concept (POC) generator with 36 HPD5 cells is under construction. The generator will consist of two stacks of 18 cells each with a central internal fuel (natural gas) reformer. Figure 9 shows the flow schematics of the POC generator which is scheduled to be tested in late May 2005.
3 Summary

Cell power enhancement was achieved by lowering both cathode polarization and ohmic resistance. Activation polarization was reduced by the use of a composite interlayer which increased the electrochemically reactive sites for oxygen reduction reaction, thereby improving the charge transfer kinetics. HPD cell design, due to reduced current path, was effective in reducing ohmic resistance. The HPD design, due to flat cell surface also offers the advantage of higher volumetric power density over tubular cells. Further power enhancement is possible by integrating different cell power enhancement results in the optimized HPD cell design. A POC generator is under construction to
prove the concept of HPD cells in a generator environment.

4 References

5 Acknowledgements
The author acknowledges the contributions of his many colleagues in Pittsburgh, USA and Erlangen, Germany whose work is presented in this paper. Financial support for this program is provided by United States Department of Energy, National Energy Technology Laboratory, the German government through BMWA, and Siemens Westinghouse Power Corporation.
Stability of Solid Oxide Electrolyser Cells

A. Hauch, S. H. Jensen, M. Menon and M. Mogensen

Material Research Department, Risø National Laboratory, DK-4000 Roskilde, Denmark

Abstract

There is an increasing interest in renewable energy, hydrogen economy and CO₂ neutral energy production. In this context a reversible Solid Oxide Cell (SOC) is potentially an interesting technology. A Solid Oxide Fuel Cell (SOFC) can be operated as a Solid Oxide Electrolyser Cell (SOEC) that electrolyses water into oxygen and the energy carrier molecular hydrogen by applying external electrical energy.

Potentially SOEC’s can be combined with already existing energy technologies to improve the efficiency. Surplus electricity produced by e.g. windmills and nuclear plants can be turned into chemical energy carriers by SOEC and later used in SOFC to produce electricity. SOEC hereby enable storage of energy from renewable energy sources such as windmills and geothermal energy.

In this work we present results from studies of SOCs that have been tested in the electrolysis mode. SOEC experiments have been performed at temperatures of 850°C and 750°C at different current densities. The degradation of the cell over time has been investigated, and a phenomenon of passivation/activation of the cell has been observed. It is shown that in electrolyser mode the cells may degrade rapidly. Necessary precautions and further improvement through future R&D are discussed.

1. Introduction

Previous results [1] have shown that it is possible to use solid oxide fuel cells for high temperature electrolysis of steam. The SOFCs produced at Risø National Laboratory are regarded as 2nd generation cells, has an oxygen electrode of strontium doped lanthanum mangenite (LSM), an electrolyte of yttria stabilized zirconia (YSZ) and a hydrogen electrode of a Ni/YSZ cermet. A considerable long-term research and development work has been conducted for these SOFCs and this has led to a production of reproducible, stable high performance SOFCs [2,3]. Moreover, the SOEC has the advantage that it is able to split CO₂ into CO and O₂, i.e. an SOEC input gas consisting of CO₂ and steam is converted to synthesis gas (CO and H₂) from which chemical energy carriers such as methane and methanol can be produced. Using SOEC it is also possible to do electrolysis of a mixture of carbon dioxide and steam and hereby produce methane. The production of methane using 2nd generation SOFCs has been obtained previously [1], but the
Encouraged by the results from long-term test for the SOFCs, the preliminary test of H₂ and CH₄ production using these same SOCs and by promising estimations of hydrogen production prices using SOECs, tests were set up to investigate the stability of SOCs when run in electrolyser mode. Here we present results from durability tests of SOEC at 750°C and 850°C, where a loss in performance is observed within a relatively short time. Furthermore we present results that illustrates that a partly activation of the cell after electrolysis test can be obtained. Finally suggestions for future R&D for improvement of the stability of the SOECs are proposed.

2. Theoretical background

Reversing the process in a SOFC leads to a production of hydrogen by electrolysis of steam. The overall reaction for the electrolysis of water is:

\[ \text{H}_2\text{O} + \text{heat} + \text{electric energy} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2 \]  

(1)

This reaction is composed of reactions. At the negative electrode the reaction is:

\[ \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}_2^- \]  

(2)

And at the positive electrode the reaction is:

\[ \text{O}_2^- \rightarrow \frac{1}{2}\text{O}_2 + 2\text{e}^- \]  

(3)

Figure 1 illustrates the basic principle for the SOEC.

![Figure 1: Basic principle of SOEC. Electrolysis of steam: \( H_2O \rightarrow H_2 + \frac{1}{2}O_2 \)]
The electrical energy supply needed for the electrolysis process is equal to the change in Gibbs free energy for the reaction:

\[ \Delta G = \Delta H - T \Delta S \]  \hspace{1cm} (4)

where \( \Delta H \) is the change in enthalpy for the reaction, \( T \) is the absolute temperature and \( \Delta S \) is the change in entropy for the reaction. The relation between the change in Gibbs free energy and the equilibrium potential, \( \varepsilon \), for the cell is given by:

\[ \Delta G = nF \varepsilon \]  \hspace{1cm} (5)

where \( n \) is the number of electrons transferred per reaction, \( F \) is Faraday’s constant and the temperature and pressure dependent equilibrium potential also called the electromotive force is given by Nernst’s equation:

\[ \varepsilon = \frac{\Delta G^\circ}{nF} + \frac{RT}{nF} \cdot \ln \left( \frac{pH_2 \cdot \sqrt{pO_2}}{pH_2O} \right) \]  \hspace{1cm} (6)

where \( \Delta G^\circ \) is the Gibbs free energy of reaction at standard conditions. Combining the two expressions for the change in Gibbs free energy gives:

\[ \varepsilon = \frac{\Delta H}{nF} - \frac{T \Delta S}{nF} \]  \hspace{1cm} (7)

\( \Delta H \) and \( \Delta S \) are positive and almost independent of temperature and therefore the equilibrium potential and the Gibbs free energy will decrease with increasing temperature as illustrated in figure 2. The change in Gibbs free energy is the electrical energy demand.

![Thermodynamic data for H₂O electrolysis](Figure 2: Thermodynamics of water electrolysis. Data are taken from [4].)
In order for the hydrogen production by high temperature electrolysis to proceed it is necessary to feed a continuous supply of steam to the negative electrode and apply an external voltage, \( V \), that is larger than the equilibrium potential \( \varepsilon \). Running SOC’s in electrolyser mode the current \( I \) is per definition negative and \(-IV\) is the consumed electric power. Due to the internal resistance in the cell the passage of current will lead to a heating of the cell equal to \((\varepsilon-V)I\). If an external voltage of \( \Delta H/nF \) is applied to the SOEC the generated joule heat is:

\[
(\varepsilon-V)I = (\Delta H/nF - T\Delta S/nF - \Delta H/nF)I = - (T\Delta S/nF)I \tag{8}
\]

which equalizes the heat removal per unit time by the endothermic electrolysis process. These thermodynamic considerations show that it is feasible to run the endothermic electrolysis reaction at elevated temperature to utilize the unavoidable joule heat. Furthermore reported results in literature state that improved kinetics is obtained for both SOFC and SOEC at high temperatures, which again argue for high temperature electrolysis [5].

The measured potential over the cell, for cell tests run in electrolyser mode, is larger than the electromotive force, \( \varepsilon \), due to different losses in the cell. The main losses giving raise to the internal resistance in the cell are: 1) The ohmic loss, often called the series resistance \( R_s \), which mainly originates from the resistance to passage of ions through the electrolyte and to a lower extent from resistance to the flow of electrons in the electrodes. 2) The polarisation losses described by the polarisation resistance \( R_p \). This resistance is related to the kinetics of electrochemical reactions at the interface layer between the electrolyte and the electrodes, and to concentration gradients [5,6].

These different losses building up the internal resistance of the cell can be investigated by electrochemical impedance spectroscopy and hereby knowledge about the nature of the resistance of the cell may be obtained.

### 3. Experimental

A Ni/YSZ supported DK-SOFC 2\textsuperscript{nd} generation cell was used for the electrolysis test. The cell has a hydrogen electrode of 15 \( \mu \)m thick Ni/YSZ cermet, a 10 \( \mu \)m thick YSZ electrolyte and a 15 \( \mu \)m thick LSM oxygen electrode. The cells are 5×5 cm\(^2\) with an active area of 16 cm\(^2\) [7]. The experimental setup for cell tests is described in detail elsewhere [7,8]. At start-up of tests the nickel oxide in the Ni/YSZ is reduced to nickel in hydrogen with a water content of 5\% at a temperature of 1000°C. After reduction of the nickel oxide a characterisation of the cell in fuel cell mode was performed to assure that the cell performance is comparable to other tested DK-SOFC 2\textsuperscript{nd} generation cells. After
this start-up procedure the electrolysis test can be started. Before electrolysis is started
the gas to the oxygen electrode is changed from air to 10 l/h of O₂. Hereby the reaction
conditions (pO₂) are kept constant at the oxygen electrode when electrolysis is started
(O₂ production at the oxygen electrode), and a transient phenomenon on the polarisation
resistance is avoided. The flow of hydrogen and oxygen to the Ni/YSZ electrode controls
the steam flow and steam content to the negative electrode and the steam content is
raised before the electrolysis is started. For the electrolysis test results presented here
utilization of H₂O was 13-14%. An overview of the test conditions for the electrolysis
tests, from which results are presented here, are given in table 1.

Table 1: Test conditions during electrolysis for the results presented here. Gas fed to the
oxygen electrode was 10 l/h O₂.

<table>
<thead>
<tr>
<th>Test</th>
<th>Figure</th>
<th>Temp.</th>
<th>Gas fed to the hydrogen electrode (Ni/YSZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A850</td>
<td>3</td>
<td>850°C</td>
<td>5.9 l/h O₂, 12 l/h H₂ (pH₂O = 0.98 atm)</td>
</tr>
<tr>
<td>B750</td>
<td>4</td>
<td>750°C</td>
<td>5.9 l/h O₂, 17.2 l/h H₂ (pH₂O = 0.70 atm)</td>
</tr>
<tr>
<td>C750</td>
<td></td>
<td>750°C</td>
<td>5.9 l/h O₂, 17.2 l/h H₂ (pH₂O = 0.70 atm)</td>
</tr>
</tbody>
</table>

Current density, i, versus cell voltage, V, was recorded before, during and after
electrolysis test simply by increasing the current stepwise while measuring the cell
voltage. From these iV-curves the area specific resistance of the cell can be calculated.

4. Results

Figure 3 shows results from electrolysis experiment A850. The cell of test A850 had and
area specific polarisation resistance of 0.27 Ωcm² at open circuit voltage (OCV) right
after start-up with 20% H₂O and 80% H₂ at the hydrogen electrode and air to the oxygen
electrode. This value for the polarisation resistance at the given conditions is comparable
to previously reported performance for these cells [7] and it is known that the cells are
very stable over long term under such inlet gas conditions and operated in fuel cell mode
[2]. In order to test the effect of high steam partial pressure (correspond to electrolyser
inlet conditions) on the hydrogen electrode the test was kept at OCV with varying steam
partial pressure for several hours. This part of the experiment A850 accounts for the first
460 hours of the test. After testing at OCV it was decided that this cell should
subsequently be used for electrolysis test. Figure 3 shows the cell voltage as a function of
time during electrolysis at 850°C with a steam content of 98% corresponding to a flow of
11.8 l/h H₂O and 2% H₂ to the Ni/YSZ, 10 l/h O₂ was led to the oxygen electrode. The
cell voltage increases from 855 mV to 1054 mV as the conditions are changed from OCV to a current density of -0.25 A/cm². Within approximately 12 hours the cell voltage reaches a maximum of 1080 mV, thereafter it decreases and stabilizes at 1058 mV. The course of the cell voltage for this electrolysis test seems to indicate that transient phenomena are taking place during the first 30 hours of electrolysis.

Figure 3: Cell voltage as a function of time during electrolysis test A850. Temperature: 850°C; the composition of the gas fed: 98% (11.8 l/h) steam and 2% H₂; a current density of -0.25 A/cm² corresponding to 14% conversion of the steam. O₂ was led to the oxygen electrode before electrolysis was started in order to keep the reaction conditions constant.

Figure 4 shows results from a similar cell tested at 750°C. For this test, B750, electrolysis was started shortly after the standard start-up procedure and characterisation of the cell was finished. Figure 4 shows the cell voltage as a function of time during electrolysis at 750°C with a steam content of 70% corresponding to a flow of 11.8 l/h and 30% H₂ to the Ni/YSZ and 10 l/h O₂ was led to the LSM electrode. Changing from OCV to a current density of -0.25 A/cm² is accompanied by jump in the cell voltage from 950 mV to 1053 mV. In the subsequent electrolysis test the cell passivates, which is observed as an increase in the measured cell voltage. After approximately 80 hours of electrolysis at constant current density the cell voltage seems to stabilize around 1280 mV.
Figure 4: Cell voltage as a function of time during electrolysis test B750. Temperature: 750°C; the composition of the gas fed: 70% (11.8 l/h) steam and 30% H₂; a current density of –0.25 A/cm² corresponding to 13% conversion of the steam. O₂ was led to the LSM electrode before electrolysis was started to keep the reaction conditions constant.

For the B750 test iV-curves were recorded in fuel cell mode 2 hours before starting electrolysis and again 16 hours after ending the electrolysis test. These iV-curves are shown in figure 5, where the arrows indicate the direction of time. The difference in cell voltage at 0 A/cm² (OCV) is caused by different gas fed to the oxygen electrode; 140 l/h air before and 10 l/h O₂ after electrolysis.

Figure 5: iV curves showing measured cell voltage as a function of current density for test B750. The curves were recorded 2 hours before (o) and 16 hours after (□)
electrolysis with a current density of $-0.25 \, \text{A/cm}^2$. For test conditions see table 1. Arrows indicate direction of time.

The slope of the iV-curves is the internal area specific resistance, $R_{\text{cell}}^\#$, for the SOEC:

$$(\varepsilon - V) = i \cdot R_{\text{cell}}$$

The area specific resistance is depending on the reactant utilization, that is the $R_{\text{cell}}$ depends on how large a part of the steam that is converted to $\text{H}_2$ on the negative electrode and to $\text{O}_2$ on the positive electrode. The overpotential will not be equal at the gas-inlet and gas-outlet, and the electrolysis will proceed with a lower rate at the gas-outlet than at the gas-inlet part of the cell. Therefore the $R_{\text{cell}}$ is corrected for steam utilization using an iterative calculation method described elsewhere [1]. Hereby conversion corrected values for the area specific resistance is obtained, hereafter given as $R_{\text{cell}}^\text{corr}$. In figure 6 the $R_{\text{cell}}^\text{corr}$ for the data in the iV-curves in figure 5 is shown. Before electrolysis the cell had a $R_{\text{cell}}^\text{corr}$ of approximately 0.4 $\Omega\text{cm}^2$ at highest current density and a significant increase in the resistance is observed for the iV-curve recorded 16 hours after the end of electrolysis test B750. Here it should be noted that the resistance for this cell, calculated from iV-curves in fuel cell mode in wet hydrogen with a humidity of 20%, at start-up was 0.36 $\Omega\text{cm}^2$ which is in agreement with results from SOFC test of similar cells and with similar test conditions [7,9].

![Figure 6: Conversion corrected area specific resistances ($R_{\text{cell}}^\text{corr}$) from iV curves in fuel cell mode for test B750 in figure 5 before (O) and after (□) 90 hours of electrolysis at 750°C with a current density of $-0.25 \, \text{A/cm}^2$. Arrows indicate direction in time.](image)

# The area specific resistance consist of a contribution from the series resistance and the polarisation resistance that is; $R_{\text{cell}} = R_s + R_p$. The area specific resistance is sometimes denoted ASR.
The iV-curve (figure 5) and the corresponding $R_{corr}^{cell}$ (figure 6) shows that recording an iV-curve in fuel cell mode have a tendency to partly activate the cell. Therefore an electrolysis test (C750) was made with similar test conditions as for B750 (see table 1). In test C750 a switch was made directly from electrolysis mode to recording an iV-curve in fuel cell mode in order to check the activation effect of iV-curves after passivation in electrolysis mode. The $R_{corr}^{cell}$ obtained from this C750 iV-curve shows a similar trend as that for test B750 (figure 6) though an even larger activation effect is observed as the $R_{corr}^{cell}$ starts at 1.33 $\Omega\text{cm}^2$ and reach a value of only 0.86 $\Omega\text{cm}^2$ when finishing the iV-curve. It should be mentioned that the cell for test C750 had a resistance of 0.35 $\Omega\text{cm}^2$ in hydrogen with a humidity of 20% at 750°C at start-up in agreement with cells tested successfully in fuel cell mode.

$R_{corr}^{cell}$ values have been obtained at start of the electrolysis, midway and just before ending the electrolysis test when the cell voltage seems to have stabilized for test A850 and B750 (figure 3 and 4). The results are given in table 2, where values for $R_{corr}^{cell}$ before electrolysis and standard values for $R_{corr}^{cell}$ at start-up for similar cells tested in fuel cell mode are also given.
Table 2: Values of measured cell resistances corrected for gas conversion, $R_{cell}^{corr}$, before, at start of, in the middle of electrolysis and when stable conditions seem to have been obtained. See table 1 for test conditions.

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Test</th>
<th>Time from start of test</th>
<th>Time at electrolysis conditions</th>
<th>$R_{cell}^{corr}$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.20±0.05 Ωcm²</td>
<td>Fuel cell test [13]: 850°C, (H₂O/H₂:25/75)</td>
</tr>
<tr>
<td>-</td>
<td>A850</td>
<td>12 hours</td>
<td>-</td>
<td>0.27 Ωcm²</td>
<td>(H₂O/H₂:25/75)</td>
</tr>
<tr>
<td>-</td>
<td>A850</td>
<td>427 hours</td>
<td>-</td>
<td>0.71 Ωcm²</td>
<td>(H₂O/H₂:25/75)*</td>
</tr>
<tr>
<td>3</td>
<td>A850</td>
<td>464 hours</td>
<td>4 hours</td>
<td>0.80 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:98/2)</td>
</tr>
<tr>
<td>3</td>
<td>A850</td>
<td>475 hours</td>
<td>15 hours</td>
<td>0.98 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:98/2)</td>
</tr>
<tr>
<td>3</td>
<td>A850</td>
<td>540 hours</td>
<td>80 hours</td>
<td>0.86 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:98/2)</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.48±0.14 Ωcm²</td>
<td>Fuel cell test [13]: 750°C, (H₂O/H₂:25/75)</td>
</tr>
<tr>
<td>-</td>
<td>B750</td>
<td>42 hours</td>
<td>-</td>
<td>0.36 Ωcm²</td>
<td>(H₂O/H₂:25/75)</td>
</tr>
<tr>
<td>4</td>
<td>B750</td>
<td>53 hours</td>
<td>4 hours</td>
<td>0.36 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:70/30)</td>
</tr>
<tr>
<td>4</td>
<td>B750</td>
<td>93 hours</td>
<td>54 hours</td>
<td>0.66 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:70/30)</td>
</tr>
<tr>
<td>4</td>
<td>B750</td>
<td>133 hours</td>
<td>104 hours</td>
<td>1.26 Ωcm²</td>
<td>i = -0.25 A/cm² (H₂O/H₂:70/30)</td>
</tr>
</tbody>
</table>

* Increase in the resistance for test A850 within the first 427 hours is mainly due to Ni agglomeration caused by a steam content of 98 % to the Ni/YSZ electrode for several hours [10].

5. Discussion

It is illustrated by the test results given in figure 3-6 that running SOC’s in electrolysis mode lead to a passivation of the cell. This passivation of the cell happens within...
relatively short time compared to similar test for 2nd generation cells run in fuel cell mode [3]. Comparing figure 3 and 4 we observe that the passivation happens over a longer period of time for the test (B750) run at 750°C compared to the test (A850) run at 850°C. Though caution should be taken not to compare the development of the cell voltage during electrolysis quantitatively for test A850 and B750 as the water content to the Ni/YSZ electrode was not the same in the two tests. The difference in water content to the negative electrode possibly influences the test results. Furthermore the cell in test A850 had a longer pre-electrolysis test period. Figure 3 indicates that transient phenomena of a timescale in the order of 30 hours are involved when testing SOC’s as electrolyser cells though similar transient phenomena was not observed for the other electrolysis tests from which results are presented here.

The iV-curves in figure 5 and the $R_{cell}^{corr}$ before and after 90 hours of electrolysis at a temperature of 750°C and relatively low current density of –0.25 A/cm² clearly illustrates that at severe passivation of the cell takes place during the electrolysis as the resistance in the cell increases significantly. The passivation of the cells run in electrolysis mode happens faster than the passivation observed for tests in fuel cell mode using similar 2nd generation cells. In these fuel cell tests the resistance in the cell increase less when the test is run for 1500 hours (750°C and 850°C, current density of 0.25 A/cm² and H2 with a humidity of 20%) than the observed increase in cell resistance for the relatively short electrolysis test presented here [3].

The values for $R_{cell}^{corr}$ given in table 2 shows that the internal resistance in the cell used in test B750 increases with a factor of 3½ within a relatively short electrolysis test period. A significantly smaller increase in $R_{cell}^{corr}$ is observed for the test A850. The observed degradation for A850 after the first 427 hours is mainly due to Ni agglomeration caused by test at OCV with a steam content of 98 % to Ni/YSZ for approximately 244 hours in total. Investigations of the effect of high steam content to the negative electrode is important as this condition is the inlet condition for electrolysis and results on this effect on the SOECs is described in [10].

For the electrolysis test represented here impedance spectroscopy was performed before and after the electrolysis test B750 with a humidity of H₂O of 20% in H₂. A description of impedance spectroscopy for electrochemical characterization can be found elsewhere [6,11]. The recorded impedance spectra have shown that the resistance due to the electrolyte is not influenced by the electrolysis. On the other hand the polarisation resistance, which relate to losses in the electrodes, increases with a factor of 3 from 0.34 Ωcm² before electrolysis to 1.1 Ωcm² after 90 hours of electrolysis. These results were reproduced in test C750. This test also led to a high polarisation resistance and the recorded impedance spectrum in H₂ with humidity of 20% after 100 hours of electrolysis gave a polarisation resistance of 1.1 Ωcm². For comparison it can be mentioned that
impedance spectra recorded before and after 1500 hours of test in fuel cell mode at 750°C and a current density of 0.25 A/cm² only led to an increase in the polarisation resistance from 0.37 Ωcm² to 0.55 Ωcm² for similar cells [3]. Furthermore a thorough analysis of the obtained impedance spectra and comparison with other reported impedance measurements [12] indicate that the passivation of the cells, when it is run in electrolyser mode and with a high steam content to the negative electrode, is both due to raise in the resistance at the Ni/YSZ electrode and at the LSM electrode.

The timescale for cation migration at T ~ 1000 K in inorganic materials such as those used in SOC’s can be estimated from the relation between the diffusion coefficient, D, and the distance the ion diffuse, x, as \( t_{\text{diff}} = \frac{x^2}{D} \) [13]. The distance of the ion diffusion is in the order of 1 µm. and the diffusion coefficient for ceramics used is \( \sim 10^{-12} - 10^{-13} \text{ cm}^2/\text{s} \) at temperatures of approximately 1100 K. This gives a time for cation diffusion in the materials in question in the order of \( t_{\text{diff}} \sim 10^8 \text{ cm}^2/10^{-12} \text{ cm}^2/\text{s} = 10^4 \text{ s} \sim 3 \text{ hours} \) which support the idea that cation migration is involved in the passivation of the electrolyser cell. A similar estimation for oxide ions result in diffusion times of seconds to few minutes and therefore the observed passivation of the cell is hardly related to oxide ion migration [13].

Both the high steam content to the negative electrode and the electrolysis can contribute to the raise in the resistance of the tested cells. Therefore future experiments will include tests using the three-electrode set-up [14] to separate the contributions to the passivation and/or degradation phenomena from the two electrodes. Furthermore development of new materials for the electrodes is in progress and cells with an oxygen electrode of LSCF\(^\#\) have been produced and are soon to be tested in electrolysis mode. Such cells with a LSCF electrode have been tested successfully in fuel cell mode previously [15].

Previous electrolysis test results at 850°C and a current density of \(-1 \text{ A/cm}^2\) on similar 2\(^{nd}\) generation cells have shown that the cell can be partly activated by operating the cell at OCV for period of time (ca. 100-170 hours) in between periods of electrolysis. Here a partly activation was also obtained. This was done not by leaving the cell at open circuit voltage but by recording iV-curves in fuel cell mode. This indicates that the loss of performance observed for the SOEC is caused by both passivation and degradation\(^\circ\). So far an understanding of the mechanisms underlying the partly activation observed in these electrolysis test have not been obtained.

\(\dagger\) Spectra were recorded at 750°C in H₂ with a humidity of 25% and O₂ was led to the oxygen electrode.

\(\#\) LSCF is strontium and cobalt doped lanthanum ferrite.

\(\circ\) The term “passivation” is used to describe reversible reduction in performance of the cell whereas “degradation” is an irreversible reduction of performance of the cell.
Prior to these SOEC tests theoretical economical calculations have been made to investigate the potential of the SOEC for hydrogen production [16]. These calculation on a SOEC stack led to an estimated production price for H₂ of 8.9 US$/GJ at an operating temperature of 750°C. It is worth to noticing, that for these calculations a resistance in the cell of 0.88 Ωcm² and a steam utilization of 71% was assumed. The production price for H₂ increase linearly with the resistance in the cells, therefore calculations made on the results presented here would lead to significantly higher H₂ production prices when the electrolyser cell needs operate for several days. The experimental results presented here compared to the economical calculations estimating the production price of H₂ using SOEC show very clearly that a lot of further research and development work is needed to improve the stability of SOEC’s and thereby make SOEC’s interesting from a commercial point of view.

6. Conclusion

The results for the electrolysis tests presented here are obtained using 2nd generation solid oxide cells. At start-up these cells have been tested to have a performance comparable to cells used for fuel cell tests. In fuel cell mode the cells have acceptable performance even after 1500 hours at 750°C [7], where as in electrolyser mode a significant loss in performance is observed after less than 100 hours of electrolysis test. For test B750, where the most severe passivation is observed, the area specific resistance in the cell after correction for steam utilisation is more than three-double from 0.34 Ωcm² to 1.26 Ωcm² within the 90 hours of electrolysis at a current density of -0.25 A/cm².

Recording iV-curves in fuel cell mode leads to a partly activation of the cell that has been used for electrolysis. This indicates that both a passivation effect and degradation contributes to the loss in performance for the tested SOECs.

Comparing previous estimation of hydrogen production prices using SOECs with the durability test results obtained, it is clear that a very significant improvement in the stability for the SOC run in electrolyser mode is mandatory to make the SOEC interesting from a commercial point of view.

Further durability tests, analysis of the processes leading the passivation of the SOEC and testing of cells with an alternative oxygen electrode of LSCF is in progress.

7. Acknowledgement

The authors thank the entire SOFC group at Risø National Laboratory for their help in this work. One of the authors (AH) gratefully acknowledges the financial support from the EU via the project “Highly Efficient, High Temperature, Hydrogen Production by

Risø-R-1517(EN)
8. References


SOFC Development Program at Haldor Topsøe/Risø National Laboratory

Haldor Topsøe A/S, Denmark
N. Christiansen, J. B. Hansen, S. Kristensen, H. Holm-Larsen
Risø National Laboratory
S. Linderoth, P. V. Hendriksen, P. H. Larsen, M. Mogensen

Abstract

Topsoe Fuel cells A/S is developing SOFC stacks and technology based on planar anode supported cells. The SOFC technology under development is based on an integrated approach in a consortium of Topsoe Fuel Cell A/S and Risø National Laboratory ranging from manufacturing of planar anode-supported cells and compact stacks to analysis of total systems. The current stack design pays attention to important parameters such as: High volume power density, low material cost, simple manufacturing, durability and reliability. The durability of the standard stack design with standard cells has been tested for more than 13000 hours including nine full thermal cycles with an overall voltage degradation rate of about 1% per 1000 hours. Recently, the degradation rate has been significantly reduced by introduction of improved stack component materials. 75-cell stacks in the 1+ kW power range have been tested successfully, so far for several hundred hours. Stacks have been delivered in a pre-reduced state to partners and tested successfully in test systems with natural gas at high fuel utilisation. The consortium of Haldor Topsøe A/S and Risø has an extended program to develop the SOFC technology all the way to a marketable product. Stack and system modelling including cost optimisation analysis is used to develop 5 kW stack modules for operation in the temperature range 700-850°C. To ensure the emergence of cost-competitive solutions, a special effort is focused on manufacturing and testing of larger anode-supported cells as well as multi stack modules. The SOFC program comprises development of next generation cells for operation at lower temperature with increased durability and mechanical robustness. Development of cells with porous metallic support and new electrode materials is in progress in order to ensure long-term competitiveness.

Background

Haldor Topsøe A/S (HTAS) and Risø National Laboratory (Risø) are jointly carrying out a development programme focusing on low cost manufacturing of flat planar anode-supported cells and stacks employing metallic interconnects. The challenge today is to integrate the cell stacks with the fuel processing system (FPS) in order to maximize the system efficiency for various fuels and applications. However, the road to success will first and foremost depend on the ability to produce high performance, cost-effective, robust cells and stacks.

HTAS has in 2002 entered into collaboration with the Danish company Wärtsilä for large-scale SOFC systems (200kW+). Wärtsilä’s responsibility in this regard includes system level integration and marketing. Establishment of partnerships such as HTAS/Risø/ Wärtsilä will serve to strengthen the technology platform and accelerate the development. The outcome of a conceptual study carried out by HTAS and Wärtsilä of a 250 kW planar SOFC system for CHP application is reported in [1].

Cell production and development

The cell production line of the HTAS/Risø pilot production line is approximately 500 cells per week and a rejection rate lower than 15% has been demonstrated. A further upscale to 1000 cells per week is underway in 2004-2005. In order to ensure a high quality and continuous cell improvement all the processing steps are computer-logged, and an extensive on-line database comprising all the relevant material, component and process details has been established in the pilot plant. The standard cells are 12 x 12 cm² with a thickness of 0.350 mm as described previously [2]. However, the cell size has also been successfully scaled up and 18 x 40 cm² cells are currently being included in the stack development for testing.

A study of the reproducibility of the cell production campaigns in 2003-4 has been carried out. This study clearly pointed out the cathode as the least reproducible component of the cell [3]. To be able to focus the further development it is necessary to be able to split up the overall cell resistance in terms emanating from individual components or processes. The analysis based on impedance spectroscopy of full cells [4] shows that the cathode is the component with the highest resistance at temperatures below 850 °C, and consequently significant effort is directed to further developing the cathode part of the cell, (see the following).

Stack Development

The HTAS/Risø SOFC stack development is focusing on a low cost reliable design based on thin multi-layers with metallic bi-polar plates (interconnects) with a high volume power density. The stack development is subdivided in a number of important tasks such as: Component machining and shaping, contacting, stack component interfaces, seals, metallic interconnects, coatings and modelling.

The properties of the metallic alloy have proven to be crucial for the stack performance and long-term durability. Oxidative behaviour and contact resistance of a significant number of potential iron-chromium based alloy candidates have been investigated [5, 6]. Furthermore, intermediate contact layer candidates have been studied in a European collaboration project [7, 8]. The initial contact resistance between a selected steel (Crofer 22APU) and a perovskite ceramic contacting plate was found to be about 7 mOhmcm² for the coated steel increasing with time at a rate of 0.5 mOhmcm²/1000h. This is acceptable for a durable stack. Thermal cycling experiments have revealed that the contact couple alloy/LSM may be thermally cycled more than five times from room temperature to 750°C with no detrimental effects.

The current HTAS stack design consists of thin-layer repeatable stack components with internal gas manifolds. Several stacks containing 5, 10, 25, 50 or 75 cells with the dimensions 12 x 12 cm² and shaped metallic interconnects have been tested in the temperature range 650-850°C with hydrogen, methane or syngas as fuels. Metallic interconnects without coatings or with ceramic and/or metallic coatings have been tested giving rise to different stack ASR and different durability properties. Recently 75-cell stacks in the 1+ kW power range have been tested successfully, so far for several hundred hours. 50-cell stacks as well as 75-cell stacks have been operated on pre-reformed natural gas with fuel utilisation up to 88
% in the 1 kW power range. A 5-cell stack with 18 x 18 cm$^2$ cells have been tested with an overall performance similar to the stacks based on 12 x 12 cm$^2$ cells.

**Long-term stack test**

A 5-cell (12 x 12 cm$^2$) stack based on thin plate metallic interconnects with a proprietary ceramic coating has now been tested for more than 12000 hours including seven full thermal cycles between room temperature and 800°C. The gas composition is 160 Nliter H$_2$ + 90 Nliter N$_2$ and 400 Nliter air per hour. The stack current at 800°C is 20 A corresponding to a stack ASR of about 1 ohmcm$^2$ and a stack volume power density of about 2 kW/liter. The thermal cycles have not affected the voltage degradation which stays at a constant low level slightly below 1%/1000 hours. This reduction of total stack power over time is predominantly due to the voltage loss of two cells in the stack. Impedance spectroscopy analysis on the stack has revealed that the series resistance is dominating until about 3500 hours operation time, whereas the polarisation resistance dominates after 9000 hours. Figure 1 shows the encouragingly modest degradation of this long term stack durability test where three out of the five cells (including interconnects) have no measurable degradation.

![Figure 1](image1.png)

**Figure 1.** Durability test (9000 hours +) of 5-cell (12 x 12 cm$^2$) stack at 800°C, 20 A.

The latest stacks use a new metallic alloy for the interconnect (Crofer 22APU) and a new perovskite coating. This improvement has reduced the overall ASR of the stack to about 0,5 ohmcm$^2$ and further improved the durability. A 5 cell stack has no measurable voltage degradation over 1000 hours and the typical initial decrease in stack voltage has also been eliminated. A 10 cell stack has been operated with a fuel utilisation of 93 % on hydrogen and 55% on methane /water. Due to the very compact stack design the stack volume power density is 2,4 kW per liter stack volume at a conservative safe operation condition of 0,38 W/cm$^2$.

![Figure 2](image2.png)

**Figure 2.** Test of a 75-cell (12 x 12 cm$^2$) in the 1 kW+ power range at 800°C, operated with 2000 Nliter H$_2$ + 1200 Nliter N$_2$ and 5075 Nliter air per hour, 28% fuel utilisation at a current of 18 A.
Development of future generation cells

The next generation of cells (3G) being developed in the HTAS/Risø consortium is thin film electrolyte cells with a ferritic stainless steel support on the anode side. The status is that 2 x 2 cm² half cells have been fabricated with dense electrolytes. Currently the effort is on up-scaling this to larger cell sizes. Work on utilizing ceria as an anode component is continued in order to enhance the robustness towards red-ox cycles and carbon precipitation. A promising new LSCF cathode material, which has an area specific resistance of 0.11 ohm cm² at 600°C on ceria electrolyte has been identified.

Modelling and system analysis

The basis case for fuel processing when the feedstock is natural gas is shown in Figure 7. The system which has been further described in [1] features an adiabatic pre-reformer for conversion of higher hydrocarbons and an anode recycle blower to provide steam and heat for the reforming reactions. The unspent fuel which is not recycled is burned in a catalytic combustor. In the system analysis the electrical efficiency at the design point is predicted to be 55%, whereas the total system efficiency is around 84%. For process simulation a 3-dimensional mathematical stack model has been established and integrated into the HTAS proprietary heat and mass balance program called GHEMB. This forms a very suitable basis for flexible and accurate system analysis. The system analysis has been further described in [9] where it has been demonstrated that a low to moderate stack degradation of about 1%, as verified experimentally above, can be counteracted by allowing a combination of reduced fuel utilisation and (from 85 to 75%), and an increased stack temperature (by 40°C) maintaining the rated output over 40,000 hours of operation and an efficiency penalty of only 3 percentage points.

Figure 3. Process flow diagram for a SOFC system.

References

Session 9 – Carbon Sequestration and Near Zero Emission

Chairman: Robert Schock, Center for Global Security Research, USA
Collaboration under the International Partnership for the Hydrogen Economy (IPHE) and the Carbon Sequestration Leadership Forum (CSLF)

Hanns-Joachim Neef
Projektträger Jülich (PtJ), Forschungszentrum Jülich, Germany
h.j.neef@fz-juelich.de

Abstract

The objectives and achievements of the International Partnership for the Hydrogen Economy (IPHE) and the Carbon Sequestration Leadership Forum (CSLF) will be described. Both are agreements between governments and aim at identifying and promoting potential areas of bilateral and multilateral collaboration on new and advanced energy technologies.

The IPHE has analysed priorities for international collaboration in research, development, demonstration and utilisation of hydrogen equipment in five areas: hydrogen production, fuel cells, hydrogen storage, codes and standards, socio-economic research. A report on such options is available and a series of IPHE conferences and workshops will pave the way to concrete collaboration projects.

The CSLF is focused on development of improved cost-effective technologies for the cost-efficient capture and safe, long-term storage of carbon dioxide (CO₂) for fossil power plants. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical issues, as well as economic, and environmental challenges. The CSLF also promotes awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

The CSLF has worked out a Technology Roadmap as a guide for the CSLF and its Members that describes possible routes to future CO₂ capture, transport and storage needs. Included are modules on the current status of these technologies, ongoing activities in CO₂ capture, transport and storage, and identification of technology gaps and non-technology needs that should be addressed over the next decade. The Technology Roadmap indicates areas where the CSLF can add value through international collaborative effort.

Both, hydrogen technologies and CO₂ sequestration, are closely connected and will serve an overall strategic framework with clean fossil fuels as a key element of a sustainable energy portfolio. International cooperation will support national and European activities.
Introduction

Germany is participating in several international initiatives which aim at a sustainable energy development. Developing a diversified portfolio of technologies and systems instead of a single dominating favourite seems to be the general consensus in the international dialogue on sustainable energy systems. However, renewables seem to be the favourable solution for the far future. Before renewables can carry the main load of a world wide energy system, other pathways have to be considered and developed. Carbon dioxide capture and storage (CCS) is an important option, mainly regarded for zero-emission power plants. However, CCS could also be applied to produce hydrogen from fossil fuels without CO$_2$ emissions. Hydrogen as an energy carrier is mainly regarded as fuel for the transport sector.

Sustainable Development

- **What we need is:**
- **Political incentives** for an additional reduction of CO$_2$-emissions
- A **portfolio of technologies** to avoid giga-tons of CO$_2$:
  - Energy savings; efficient conversion and end-use technologies
  - Renewable energies
  - CO$_2$ capture and storage
  - Hydrogen technologies
  - Advanced transmission and distribution technologies for all energy carriers
  - **Advanced nuclear reactors, fusion**
  - ..... New ideas and basic research

In Germany, the 5th Federal Programme for Energy Technology and Research is under preparation and will contain the main elements of a portfolio for sustainable development.

National Initiatives

- **The 5th Federal Programme for Energy Technology and Research** is under preparation:
  - Energy Efficiency
  - Modern power plant technology based on COORETEC – an R&D concept for electricity from fossil fuels with CO$_2$ capture and storage
  - Renewable Energies
  - Fuel Cells and Hydrogen
Germany is participating in and influencing the European and international programmes and initiatives on energy technologies.

### International Initiatives

#### 2003:
Germany joins IPHE, CSLF and additional IEA activities

### European Initiatives

#### 2004:
- European Hydrogen and Fuel Cell Technology Platform (HFP) established with strong German participation
- European Research Area (ERA-NET) project HY-CO started
- European Technology Platform for Zero Emission Fossil Fuel Power Plants under establishment
- ERA-NET project FENCO will start soon

#### 2005:
- 7th Framework Programme in preparation

The International Partnership for the Hydrogen Economy and the Carbon Sequestration Leadership Forum are two international agreements, initiated by the United States, in which Germany participates. Both are described and first experiences from a German viewpoint are reported.

### International Partnership for the Hydrogen Economy (IPHE)

The International Partnership for the Hydrogen Economy (IPHE) was signed in November 2003.

#### IPHE Goals

- Efficiently organize and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy.
- Forum for advancing policies, and common codes and standards that can accelerate the cost-effective transition to a global hydrogen economy to enhance energy security and environmental protection.

The IPHE provides a mechanism for Partners to organize, coordinate and implement effective, efficient, and focused international research, development, demonstration and commercial utilization activities related to hydrogen and fuel cell technologies. The IPHE provides a forum for advancing policies, and common technical codes and standards that can accelerate the cost-effective transition to a hydrogen economy.
economy; and it educates and informs stakeholders and the general public on the benefits of, and challenges to, establishing the hydrogen economy.

Currently, the IPHE has 17 Partners.

A Steering Committee governs the overall framework, policies and procedures of the IPHE, periodically reviews the programme of collaborative activities, including a review of the organizational structure if necessary.

An Implementation and Liaison Committee identifies promising directions for research, development, demonstration, and commercial use; reviews the progress of collaborative projects; provides technical assessments for policy decisions, pursues international codes and standards and safety protocols, and makes recommendations to the Steering Committee on needed actions.

Both Committees are concerned about involving stakeholders from Partner countries in IPHE activities and to create collaboration between industry, science and policy communities. German experience has shown that the main responsibility to involve stakeholders is with the national delegates of the Committees. In Germany, the National Coordination Office Jülich for Hydrogen and Fuel Cells (NKJ) was established in late 2004 to support the information flow on national, European and international activities.

The principal coordinator of the IPHE’s communications and activities is the IPHE Secretariat. The U.S. Department of Energy serves initially as the IPHE Secretariat unless otherwise decided by consensus of the Partners.

The voluntary nature of successful international cooperation applies to both IPHE and CSLF, which will be described later: each Partner’s participation in the activities is subject to the availability of funds, personnel and other resources.

By creating the IPHE, the Partners have committed to accelerate the development of hydrogen and fuel cell technologies to improve their energy security, environmental protection and economic development.

After more than one year of operation, coordination through the IPHE starts to leverage scarce international RD&D funds. The cost of the hydrogen and fuel cell research programmes of the IPHE Partners will be reduced through information sharing that facilitates efficiencies in their research and demonstration programmes.
IPHE Projects – from definition to implementation

- Bottom-up process through „Scoping Papers“:
  - Priority topics were determined by the Implementation and Liaison Committee (ILC) (November 2003)
  - International Teams (Task Forces) defined project opportunities (2004)
  - Workshops and Conferences to develop work plans for projects (2005)
  - Modalities and financing for concrete projects need to be agreed upon (2005...200x)
  - Start of projects (200x)

IPHE Priority Topics

- Innovative and Alternative Production Processes of Hydrogen
- Collaborative Fuel Cell R&D
- Hydrogen Storage
- Collaborative Activities on Regulations, Codes and Standards for the Hydrogen Economy
- Socio-economics of Hydrogen

At its November 2003 inception meeting the IPHE Implementation-Liaison Committee identified the following priority areas for collaborative research and development among the IPHE Partners:

- Hydrogen Production
- Hydrogen Storage
- Collaborative Fuel Cell R&D
- Hydrogen and Fuel Cell Regulations, Codes and Standards
- Socioeconomics of Hydrogen

The Committee established Task Forces for each research priority area. The Task Forces, composed of a lead author and experts from IPHE countries, produced Scoping Papers that summarize the current state of technology, identify technical barriers to commercial deployment, and further prioritize concrete projects, events and actions to be undertaken by IPHE Partners. The Scoping Papers are “living” documents that will be updated as research and demonstration projects are completed and new priorities emerge. The Scoping Papers, in the version of January 2005, can be downloaded from the IPHE Homepage. Several workshops and conferences are scheduled for the remaining months of 2005 with the aim of establishing work programmes for collaborative projects in the priority areas. This “bottom-up” process is involving national experts to define research needs and fosters implementation of large-scale, long-term public-private cooperation to advance hydrogen and fuel cell technology and infrastructure research, development, demonstration and commercial use.

A “top-down” approach was initiated by the IPHE Secretariat by requesting from the national delegates of the IPHE Committees proposals for projects to be performed under IPHE. Some 20 proposals are now being evaluated by a team of experts according to criteria agreed upon in the Committees.
IPHE Projects – from definition to implementation

- Top-down process by projects proposals requested by the IPHE Secretariat:
  - IPHE Secretariat requested project proposals both from Steering Committee and Implementation-Liaison Committee (early 2005)
  - About 20 projects proposals were submitted (until April 2005)
  - ILC established a „Project Evaluation Team“ to evaluate proposals according to agreed upon guidelines and criteria
  - Project evaluation and approval by IPHE Committees (2005-200x)

IPHE Priority Topics

- Innovative and Alternative Production Processes of Hydrogen
- Collaborative Fuel Cell R&D
- Hydrogen Storage
- Collaborative Activities on Regulations, Codes and Standards for the Hydrogen Economy
- Socio-economics of Hydrogen

It is expected that in September 2005 the Steering Committee will agree on a number of projects originating from the Scoping Papers and the evaluation of the proposals.

The process from signing the IPHE Terms of Reference to concrete, substantial and meaningful collaboration projects, involving a number of IPHE Partners and their stakeholders seems to be slow. However, progress needs time, especially when taking into consideration the great number of IPHE Partners with different viewpoints, resources and management systems. The dialogue and information sharing in the Committees and Task Forces on national programmes and policies are achievements which should not be underestimated.

As an example, a successful exchange on experiences with transport and stationary demonstration projects took place in 2004 and 2005. The presentations are available on the IPHE Homepage as well.

Carbon Sequestration Leadership Forum (CSLF)

CSLF Mission
The MISSION of CSLF is technology oriented

- The CSLF is a framework for international co-operation in research and development for the separation, capture, transportation and storage of CO₂

The Carbon Sequestration Leadership Forum is an international initiative that is focused on development of improved cost-effective technologies for the separation and capture of carbon dioxide for its long-term safe storage. The purpose of the CSLF is to make these technologies broadly available internationally; and to identify and address wider issues relating to carbon capture and storage (CCS). This includes promoting the appropriate technical, political, and regulatory environments for the development of such technology.
Global climate protection is one of the objectives of the CSLF.

Why CSLF?

Global Climate Protection

- World CO₂ emission will increase by more than 100% over the next five decades – if we don’t do better: an increase from 25 Gt CO₂ in 2000 to 55 Gt CO₂ in 2030
- To achieve a sufficiently low level of 550 ppm CO₂ by 2050, CO₂ emissions should decrease and not increase
- CO₂ capture and storage could contribute significantly to emission reduction of more than 30 Mt CO₂ per year

Energy supply security and the integration of non-industrial countries into the global process of reducing greenhouse gas emissions are important objectives for the CSLF.

Why CSLF?

Energy supply security and non-industrial countries

- CO₂ capture and storage would result in sustainable use of coal
- If coal remains a viable energy option, energy supply security would be increased
- This is of importance for countries like China: however, if CO₂ policies are limited to industrialized countries, the role of CO₂ capture and storage is significantly reduced on a global scale
- Technology transfer is essential – and should start immediately
- Policy harmonisation is essential – not yet clear when and how

The CSLF Charter was signed in June 2003 by representatives of 13 countries and the European Commission. Since then, Germany, South Africa, and France have joined, bringing the total number of members to 17. Denmark requested membership some months ago and will be welcomed as 18th member at the next CSLF meeting in September 2005.
The Charter establishes a broad outline for cooperation with the purpose of facilitating development of cost-effective techniques for capture and safe long-term storage of carbon dioxide, while making these technologies available internationally.

The activities of the CSLF are conducted by a Policy Group, which governs the overall framework and policies of the CSLF, and a Technical Group, which reviews the progress of collaborative projects and makes recommendations to the Policy Group.

The activities of CSLF projects specifically include:

- Information exchange and networking,
- Planning and road-mapping,
- Facilitation of collaboration,
- Research and development,
- Demonstrations,
- Public perception and outreach,
- Economic and market studies,
- Institutional, regulatory, and legal constraints and issues,
- Support to policy formulation, or
- Other issues as authorized by the Policy Group.

The CSLF website is available at: http://www.cslforum.org with members area.
A first set of projects to be operated under the CSLF was presented to the joint meeting of the Policy and Technical Groups in January 2004. Projects were reviewed and several of them were nominated for endorsement by the CSLF. The endorsement of ten projects was announced at the CSLF meeting in September 2004.

**ARC Enhanced Coal-Bed Methane Recovery Project**
This link goes to the project fact sheet. The ARC Enhanced Coal-Bed Methane Recovery Project is a pilot-scale project (3 test wells) located in Alberta that will evaluate a previously developed process of CO2 injection into deep coal beds for simultaneous sequestration of the CO2 and liberation (and subsequent capture) of coal-bed methane.

**CANMETF Energy Technology Centre (CETC) R&D Oxyfuel Combustion for CO2 Capture**
This is a pilot-scale project (0.3 megawatt-thermal) located near Ottawa, Ontario, that will demonstrate oxyfuel combustion technology with CO2 capture. The goal of the project is to develop energy-efficient integrated multi-pollutant control, waste management and CO2 capture technologies for combustion-based applications and to provide information for the scale-up, design and operation of large scale industrial and utility plants based on the oxy-fuel concept.

**CASTOR**
The CASTOR project is endorsed by the CSLF. CASTOR, "CO2 from Capture to Storage", is a European initiative grouping 30 partners (industries, research institutes, and universities) representing 11 European countries, including CSLF members France and Norway. The project is partially funded by another CSLF member, the European Commission, under the 6th Framework Program. CASTOR’S overall goal is to develop and validate, in public/private partnerships, all the innovative technologies needed to capture and store CO2 in a reliable and safe way.

**CO2 Capture Project**
This is a pilot-scale project that will continue the development of new technologies to reduce the cost of CO2 separation, capture, and geologic storage from combustion sources such as turbines, heaters and boilers. CCP is an international public private R&D partnership.

**CO2 Separation from Pressurized Gas Stream**
This is a small-scale project that will evaluate processes and economics for CO2 separation from pressurized gas streams. Testing will utilize membranes developed in Japan at a test facility near Pittsburgh, Pennsylvania, United States. The proposed project, which began in 2003 and is scheduled for completion in 2006, will evaluate primary promising new membranes under atmospheric pressure. The next stage is to improve the performance of the membranes for CO2 removal from the fuel gas product of coal gasification and other gas streams under high pressure.

**CO2SINK**
This is a pilot-scale project that will test and evaluate CO2 capture and storage at an existing natural gas storage facility near Berlin, Germany, and in a deeper land-based saline aquifer. A key part of the project will be monitoring the migration characteristics of the stored CO2.

**CO2STORE**
This large-scale project is a follow-on to the current Sleipner project, which involves injection of about one million metric tons per year of CO2 into an offshore geologic saline formation beneath the North Sea. This next phase will involve continuation of monitoring of the field to track CO2 migration (involving a seismic survey) and additional studies to gain further knowledge of geochemistry and dissolution processes. There will also be several preliminary feasibility studies for additional geologic settings (in Wales, Germany, Denmark, and Norway) of future candidate project sites. The goal of the project is to develop sound scientific-based methodologies for the assessment, planning, and long-term monitoring of underground CO2 storage, both onshore and offshore.

**Frio Project**
This link goes to the Bureau of Economic Geology at the University of Texas at Austin. The Frio Project is a pilot-scale project located near Houston, Texas, that will demonstrate CO2 sequestration in an on-shore underground saline reservoir. The project involves injecting relatively small quantities of CO2 into the reservoir and monitoring its movement in the formation for several years thereafter.

**ITC CO2 Capture with Chemical Solvents**
This is a pilot-scale project (4 metric tons per day CO2 capture) located on a flue gas slipstream of a lignite-fuelled power plant near Regina, Saskatchewan, Canada, that will demonstrate CO2 capture using chemical solvents. Supporting activities include bench- and lab-scale units that will be used to optimize the entire process using improved solvents and contactors, develop fundamental knowledge of solvent stability, and minimize energy usage requirements. More than $5 million has so far been spent on construction of the pilot facility at the project site and another $3 million on a pilot plant (1 metric ton per day CO2 capture) at the University of Regina where additional testing is taking place. The goal of the project is to develop improved cost-effective technologies for separation and capture of CO2 from flue gas. Current research is demonstrating significantly reduced regeneration energy requirements.

**Weyburn II CO2 Storage Project**
This is a commercial-scale project that will utilize CO2 for enhanced oil recovery at a Canadian oil field. The goal of the project is to determine the performance and undertake a thorough risk assessment of CO2 storage in conjunction with its use in enhanced oil recovery.

The Policy Group reviewed legal, regulatory and financial issues with regard to CCS such as environmental regulations, intellectual property provisions, and trans-boundary issues. A special task force examined these issues and reported its findings to the CSLF Groups in September 2004. Reports are available on the CSLF Homepage.

As for the IPHE, the CSLF Groups are concerned about the involvement of stakeholders. Stakeholder involvement in the process of developing commercially competitive and environmentally safe CCS technologies is critical for the success of the CSLF. In Germany, close connection between CSLF delegates
and the representatives of the national COORETEC activities, especially the COORETEC Advisory Board, fosters involvement of national stakeholders.

As part of its mission under the CSLF Charter to "identify promising directions for research", the CSLF Technical Group has produced a Technology Roadmap that is intended to act as a guide for the CSLF and its Members in describing possible routes to future carbon dioxide capture, transport and storage needs. This Roadmap will indicate areas where the CSLF can make a difference and add value through international collaborative effort. This roadmap, available on the CSLF Homepage, includes:

- Information from applied R&D projects to underpin the framework
- Information from demonstration (pilot projects)- developed and underway
- Critical milestones to be achieved in the first 10 years of CSLF operation (until 2013)
- A mechanism for feedback from national programmes and vice versa to develop "a living document"

Identifying gaps in the development chains for CO₂ capture and transport technologies and for CO₂ monitoring and verification of storage was the task of two groups of experts. Another group was asked to review and identify standards with regard to storage capacity measurement. Results were discussed end of April 2005 at a Technical Group meeting and will be reported to the CSLF Groups in September 2005. New projects and activities, in addition to the ten CSLF projects mentioned earlier, are expected to be evaluated by a CSLF Project Initiation and Review Panel and approved by the Technical and Policy Groups.

Identifying gaps in the development chains for CO₂ capture and transport technologies and for CO₂ monitoring and verification of storage was the task of two groups of experts. Another group was asked to review and identify standards with regard to storage capacity measurement. Results were discussed end of April 2005 at a Technical Group meeting and will be reported to the CSLF Groups in September 2005. New projects and activities, in addition to the ten CSLF projects mentioned earlier, are expected to be evaluated by a CSLF Project Initiation and Review Panel and approved by the Technical and Policy Groups.
IPHE and CSLF: a promising team for energy systems for the long term

Energy systems of the future must be cleaner and much more efficient, flexible, and reliable to meet the growing global demand for energy. A hydrogen economy offers a potential contribution to satisfying the global energy requirements while reducing the dependency on imported petroleum and natural gas.

An ideal hydrogen economy is one in which hydrogen is produced cleanly and cost-effectively from renewables. However, most hydrogen scenarios and roadmaps realistically start from the today’s fossil fuel based economy where hydrogen is produced mainly by reforming natural gas and to a lesser extend by electrolysis. When using natural gas and coal as fuel for producing hydrogen, CO2 will be released. In combination with CO2 capture and storage the potential for reducing greenhouse gas emissions can be extended to nearly eliminating such emissions.

Although the main focus of the CSLF is on CO2-free electricity production from fossil fuels, mainly coal, CO2 capture and storage is as well an important technology for producing hydrogen from fossil fuels. Near-zero emissions for fossil fuel power production is also in the core of the German COORETEC approach which will be reported later. Modelling energy technology and policy with a focus on carbon dioxide capture and storage will be the subject of the following presentation of the IEA.

National, European and international programmes and initiatives on hydrogen and fuel cell technologies and on fossil fuel power production with nearly zero emission of CO2 are underway and are developing technologies for sustainable energy systems in the long term. CSLF and IPHE are a promising team for an overall strategic framework with clean fossil fuels as a key element of a sustainable energy portfolio.
References

- IPHE Homepage: http://www.iphe.net/

- CSLF Homepage: http://www.cslforum.org/

- NKJ Homepage: http://www.nkj-ptj.de/ (in German)

- Near Zero Emission Fossil Fuel Based Power Generation - R&D Activities within the EU;
  Angel Perez Sainz; Head of Unit Energy Production and Distribution, DG Research, European
  Commission
  COORETEC Workshop, Leipzig, 10-11th March 2005
Modelling Energy Technology and Policy
Role of alternative fuels and drive systems in the transportation sector

Dolf Gielen, Lew Fulton, Jacek Podkanski, Giorgio Simbolotti and Fridtjof Unander
International Energy Agency, Paris
Tel. +33 140576657; Fax +33140576759; E-mail dolf.gielen@iea.org

Abstract
Enhanced supply security and CO2 policies can result in substantial changes in the transportation fuel market by 2050, even at oil prices of 29 to 35 USD/bbl. IEA analysis suggests that synfuels from coal, natural gas and biomass can become technologically and economically feasible substitutes for oil refinery products, while energy efficiency measures have the potential to reduce oil demand even further. The share of transportation fuels from conventional oil can decline to 40% by 2050, if proper new policies are introduced. Hydrogen can play an important role if the capital cost can be brought down sufficiently.

1 Introduction
Energy policies are aiming for an environmentally acceptable, secure and affordable energy supply. This combination poses a challenge, and important changes on both the supply side and the demand side will be needed in the coming decades. New energy technologies will be needed. This paper discusses the future role of alternative fuels and drive systems in the transportation sector. The analysis covers issues of great importance for energy policy makers such as supply security and CO2 emissions. Special attention is paid to the competition between hydrogen and biofuels, and to the need for CO2 capture and storage (CCS) for transportation fuels production. The analysis illustrates how partial equilibrium models such as the ETP-MARKAL model can be used for energy policy analysis. This study has been carried out within the framework of the activities of the IEA Hydrogen Coordination Group.

This analysis is based on the Energy Technology Perspectives (ETP) model of the International Energy Agency. This is a MARKAL-type partial equilibrium model of energy supply and demand (Loulou et al., 2004). The ETP model covers the world split in 15 regions with different natural resource, economic activity, and energy policy goals. Regional differences, e.g. in terms of energy trading and import dependency are accounted for. This affects the perspectives of the technology options. The time period is 2000-2050. The energy system is optimized in 5-year steps in a perfect foresight approach. The main result is a quantitative assessment of the potential role of emerging energy technologies.

2 The hydrogen contribution to energy policy targets
The recent hike of oil prices has again raised the interest in oil alternatives. While the long-term projections of the IEA suggest an oil price between 29 and 35 USD/GJ for 2030 (IEA 2004a), the
potential to expand production in the Middle East and the impact of this uncertainty on oil prices is a source of concern. This expansion is critical to meet rising demand. Alternative drive systems and fuels can reduce the need for oil imports from the Middle East markedly.

The analysis of oil alternatives focuses on transportation fuels because the transportation fuel market (including international marine bunkers) represents about 53% of the world refinery product demand. If refinery use, bitumen for asphalt and lubricants are included, the share of the transportation sector in the oil market rounds to 60%. This share is projected to increase further in the coming decades.

Hydrogen (H₂) has received a lot of attention as a potential transportation fuel. Global governmental spending on hydrogen and fuel cells R&D is about 1 billion a year, which represents one eighth of the total public energy R&D budget in the IEA countries (IEA, 2004d). Hydrogen is not a primary energy carrier. It can be produced from natural gas, coal, biomass and electricity. Electricity, in turn, can be produced from many primary energy sources. The fact that oil is not needed and that various types of feedstock can be used for hydrogen production offers important benefits for energy diversification and supply security in case hydrogen is introduced as an oil product substitute.

While hydrogen itself is a CO₂-free energy carrier, the hydrogen-related emissions depend on the primary energy source and the hydrogen production process. Hydrogen production from fossil fuels with CO₂ capture and geological storage (CCS) could become a viable option if large-scale CCS will be proved to be technically and economically feasible in the next decade(s) (IEA, 2004b). Hydrogen from electrolysis is CO₂-free if it is based on electricity from nuclear and renewable sources. It is evident that for the time being such electricity represents a small share of total electricity production and would be neither available nor sufficient for significant hydrogen production. Such CO₂-free electricity must first go to the grid, possibly followed by hydrogen production at a later stage.

The introduction of hydrogen in the transportation sector is to some extent linked to the introduction of fuel cell vehicles (FCV). Such vehicles would have efficiency two to three times as high as current internal combustion engine vehicles (ICEVs). Fuel cells however are not a precondition for hydrogen use. Hydrogen can be burned in conventional combustion engines as well with efficiency gains with respect to oil products. Yet hybrid cars allow a 20-40% efficiency gain, compared to conventional cars, depending on the drive cycle characteristics. Hydrogen hybrids would therefore increase the vehicle efficiency, compared to existing conventional ICEVs. While hybrid cars can be considered as a “proven technology” with limited additional cost, FCVs are currently much more expensive and significant technology improvements and time are required to make their cost economically competitive. In addition to the cost of the fuel cell engine, a major technical challenge is onboard hydrogen storage to allow the vehicle a reasonable driving range. Apart from passenger cars, delivery trucks and buses could represent niche markets for hydrogen-fuelled FCVs as they could stand higher investment cost due to the more intense use of the vehicles, and offer more space for hydrogen storage.

Hydrogen could also be used as a fuel for airplanes with minor adjustments to the jet turbines. The main challenge here is the storage of liquid hydrogen. Hydrogen instead of jet kerosene would entail an efficiency penalty of 10-25%, and it would reduce the carrying capacity per airplane. Hydrogen would require flying at lower altitudes in order to avoid climate impacts of water emissions at higher altitudes. This increases the fuel consumption and flight time.

Hydrogen is also considered as a CO₂ emission free fuel for stationary applications, either centralized or decentralized, in both the residential and industrial sectors. These options however are beyond the scope of this paper.
3 Alternative ways to meet energy policy targets in the transportation sector

Hydrogen is not the only option to meet energy policy targets in the transportation sector. However, only a few options can meet the joint targets of enhanced supply security and CO₂ emissions reduction (figure 1, Gielen and Unander, 2005). Apart from hydrogen and biofuels, energy efficiency measures seem the only viable option. They can be combined with hydrogen and biofuels, for example if hybrid vehicles are used. However the energy efficiency of a hydrogen FCV will be higher than the efficiency of a hybrid vehicle.

Figure 1: Transportation fuel supply options, and their contribution to energy policy targets

A wide range of biofuels can be discerned such as established sugarcane ethanol, biodiesel from oil crops over lignocellulosic ethanol, and more speculative technologies such as Fischer-Tropsch synthesis to produce gasoline and diesel, and hydrothermal liquefaction. There is no single best option, and biofuel cost will depend on the production volumes, technological progress and the availability of feedstocks. A major advantage of biofuels is their compatibility with the current supply infrastructure, and the need for limited vehicle adjustments. It is clear that a non negligible potential exists for low-cost biofuels, but it is not yet clear how substantial this potential is. In 2003, world fuel ethanol production amounted to 28 billion litres. At 21.1 MJ/l (LHV), that equals 0.4 mb/d (about 0.5% of global oil consumption). The production is mainly concentrated in Brazil and the United States. Our preliminary estimate for sugar cane ethanol potential is a maximum of 10-15 percent of world gasoline demand in 2050, at current projected gasoline demand levels in that year. This would require a very aggressive expansion of cane and cane ethanol production in those countries that grow cane.

The primary biomass and the land that is needed for biofuels production can also be used for other purposes, e.g. biomass can be used for electricity production or for residential heating. Moreover
biomass plantations should not be expanded at the expense of existing forests and wetlands because of the CO₂ impact⁴ and the environmental consequences of such expansion. Therefore, biofuels have various competitors for biomass and land use, as well as they have competitors (e.g., hydrogen) as transportation fuels. Given such complex interactions, an energy systems approach is needed for assessing different fuel and vehicle alternatives. Here we describe the systems approach we take for hydrogen.

### 4 Hydrogen in the ETP model

The model structure for hydrogen production, distribution and use in the ETP model is shown in figure 2. A large number of supply options have been considered. A key issue for the transition to hydrogen is that the cost of these options will depend on the scale of production. For the sake of this study, only the optimal scale of production has been considered in the analysis. So this analysis does not account for certain transition issues such as the chicken-or-egg problem. This will be a next step in the analysis. The goal here is to explore the long term potential of a hydrogen energy system and what such a system should look like.

**Figure 2: Hydrogen supply and demand in the ETP model**


⁴ Biomass plantations may enhance the annual yield per hectare, compared to natural forests. However this causes undesirable environmental impacts such as a reduction of biodiversity.

---

Risø-R-1517(EN) 250
In the ETP model, the transportation sector module builds on previous work carried out by the IEA together with the World Business Council on Sustainable Development (WBCSD, 2004). Cars, SUVs and Pick-ups, medium sized freight trucks, heavy trucks, airplanes and a number of other modes are modeled separately. Within each category, competing drive/fuel combinations have been considered, which differ in energy efficiency, emissions and cost. The model selects options based on least life-cycle cost. Hurdle rates have been applied to the vehicle cost to reflect consumer time preferences. They range from 12% in Japan to 28% in Africa. The discount rates are lower for industrial investment in fuels production processes. This reflects actual decision making rationale. A consequence is that capital intensive options on supply side are favoured compared to capital intensive options on the consumer side. Also, the annual vehicle kilometrage has been specified by region, based on the current distances driven. For example for cars, these range from 17,600 km in North America to 8,000 km in India. A higher mileage implies that capital costs are less important. The combination of different fuel prices, fuel taxes, investment cost and mileage make that certain options would seem attractive in certain regions while they are not attractive in other regions.

In many countries transportation markets are subject to major government intervention through regimes that favor or tax certain fuel types. This includes VAT, excise tax, and taxes on certain drive systems (e.g. diesel engines) or progressive taxes on engine volumes. For example gasoline taxes (excise tax plus VAT) range from 3 USD/GJ in the US to 29 USD/GJ in the UK, a difference of one order of magnitude (IEA 2004c). The UK tax represents a threefold increase of gasoline supply cost. In many countries the tax on diesel fuel is lower than on gasoline, thus favoring the use of diesel. Also, ethanol fuel and natural gas is exempt from fuel taxes or subject to preferential tax regimes in many countries. Such tax exemptions pose a strong incentive to use such alternative fuels. In principle, tax revenues are needed, e.g. to pay for the transport infrastructure, and exemptions should reflect externalities such as enhanced supply security or reduced environmental impacts. Obviously energy efficiency measures and smaller cars will be much more attractive in a regime with high fuel taxes. This is evident from the efficiency gap between the US and Europe, where US cars use 40% more fuel.

For the model analysis it is assumed that the regional taxes remain at their current levels in absolute terms through the period 2000-2050. The diesel tax in Europe is set at 75% of the gasoline tax. For alternative fuels (CNG, LPG, DME, ethanol, methanol) it is assumed that the tax is gradually introduced and reaches 75% of the gasoline tax by 2050. Synthetic gasoline and diesel (fuels produced via so-called Fischer-Tropsch synthesis) are assumed to be taxed like gasoline and diesel from oil, as it will be very difficult to make a difference. This approach of gradually increasing taxes ensures that governments continue to receive revenues as the use of alternative fuels expands.

Finally CO₂ capture and storage was considered for all major transportation fuel production processes. This is of critical importance for the environmental impact of a number of fuel options. The large-scale feasibility of underground CO₂ storage is currently being explored by industrial demonstration projects. This is a key issue that deserves detailed analyses.

5 ETP model analysis – Key assumptions

The model analysis includes four parameters:

- Security policy targets;
- CO₂ reduction incentives;
- Biomass availability; and
- The hurdle rate for investments in the transport sector;

Various measures can be envisaged for improving energy security. For the sake of this analysis, the maximum share of transport fuels from imported oil was varied. This reflects possible concerns...
regarding the oil dependency on the Middle East. This constraint could reflect policies that promote indigenous production of transportation fuel alternatives, or indigenous production of conventional and non-conventional oil. While such targets can be varied by region, for the sake of this analysis the target were identical constant across all model regions. It was assumed that constraints would be gradually introduced from 2005 onwards, and they attain their maximum level in 2050. Either 50% of 67% of total transportation fuels is not derived from imported oil. This means at most 50% and 33%, respectively, of all transportation fuels is based on imported oil.

Policies for CO₂ mitigation have been simulated through an emissions reduction incentive. The 50 USD/t CO₂ incentive level was chosen for more detailed discussion because it roughly represents emission stabilization in the period 2000-2050, or a halving the emissions by 2050, compared to the BASE scenario (IEA, 2004b). In the industrialized countries, the introduction of incentives is assumed to start in 2005, reach the level of 50 USD/t CO₂ by 2015, and stabilize thereafter. In developing countries, the policy is delayed by 15 years and the penalty reaches its maximum level by 2030.

While a 50 USD/t CO₂ penalty is a high burden for developing countries, it could likely be applied in the long term, given the environmental concerns and the fast rate of economic development of many such countries. In the model scenarios, per capita GDP in all regions except Africa by 2050 is close to or even higher than the per capita GDP in OECD Europe in 2000.

The quantities of biomass that will be available in the future constitute a major uncertainty. The reference calculations assume a potential availability that increases gradually to 200 EJ primary biomass per year by 2050. This should be compared to the present total primary energy use of more than 400 EJ per year, and a present biomass use of more than 40 EJ per year. The biomass supply potential is split into 11 classes, ranging from dedicated plantations on agricultural land to increased recovery from existing forests. However future biomass availability is a major uncertainty. Competing land use for food production and an uncertain increase of agricultural yields are the main uncertainties. In a sensitivity analysis, the biomass supply potential is reduced to 100 EJ per year.

Any option in the transport sector depends critically on capital cost of vehicles. This is elaborated in table 1, where ETP model data are used to compare gasoline ICEs and various hydrogen vehicles. The investment cost has been annualised using an annuity of 15%, which equals roughly a discount rate of 12%. This analysis shows that energy efficiency measures for gasoline cars are cost-effective, but hydrogen vehicles would require an incentive of 130 USD/t CO₂ to break even. However, as the cost of the hydrogen hybrid and hydrogen FCV are dominated by the investment annuity, a lower discount rate would result in a much more favourable valuation.

Data in table 1 assume a cost reduction for fuel cell engines to the level of gasoline ICEs. However, a fuel cell vehicle has additional components such as the electric engine and the hydrogen storage system. The data for these components were based on a recent European study (CONCAWE, 2003) including cost reductions over the next 50 years. The fuel cell engine cost decline in this scenario to 50 USD/kW. It is assumed that the cost for a hydrogen tank for a fuel cell vehicle decline to 2000 USD, and the electric engine costs 2000 USD. These two components alone cost almost the same as a conventional ICE drive system, and the whole drive system costs 105 USD/kW. In a separate scenario, more optimistic cost assumptions were used (Ogden et al., 2004). The cost of the fuel cell decline to 35 USD/kW, the cost of the hydrogen storage tank decline to 350 USD/kg and the cost of the electromotor system declines to 1200 USD per vehicle. The total cost of the drive system amounts to 65 USD/kW. It should be noticed that such cost reduction would require major technical breakthroughs.
Table 1: Comparison of vehicle alternatives, 15% annuity, European fuel taxes, 2030-2050 cost data. ETP model data assuming FC cost declining to 50 USD/kW.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline ICE</td>
<td>0</td>
<td>0</td>
<td>252</td>
<td>594</td>
<td>846</td>
<td>1.73</td>
<td>-825</td>
</tr>
<tr>
<td>Gasoline adv.ICE</td>
<td>500</td>
<td>75</td>
<td>227</td>
<td>401</td>
<td>703</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>Hydrogen adv.ICE with liquid storage</td>
<td>1800</td>
<td>270</td>
<td>469</td>
<td>469</td>
<td>1208</td>
<td>0.00</td>
<td>210</td>
</tr>
<tr>
<td>Hydrogen hybrid ICE with 700 bar gas storage</td>
<td>3390</td>
<td>509</td>
<td>282</td>
<td>282</td>
<td>1073</td>
<td>0.00</td>
<td>130</td>
</tr>
<tr>
<td>Hydrogen FCV with 700 bar gas storage</td>
<td>5625</td>
<td>844</td>
<td>245</td>
<td>245</td>
<td>1334</td>
<td>0.00</td>
<td>280</td>
</tr>
</tbody>
</table>

A total of eight scenarios were analysed to accounts for the various options described above. Their acronyms and characteristics and are listed below and in table 2. The following acronyms are used:

- BASE: base line scenario
- NFT: no fuel tax
- GLO50: 50 USD/t CO2 incentive
- SEC50, SEC67: 50% and 67%. Supply security oil import constraints
- BIO: low biomass potential
- DISC: low discount rate
- LCFCV: low cost fuel cell vehicles

Table 2: Scenario characteristics

<table>
<thead>
<tr>
<th>Fuel tax CO2 incentive [USD/t]</th>
<th>BASE NFT</th>
<th>BASE GLO50</th>
<th>GLO50 SEC50</th>
<th>GLO50 SEC67</th>
<th>GLO50 SEC67 BIO</th>
<th>GLO50 SEC67 BIO DISC</th>
<th>GLO50 SEC67 BIO DISC LCFCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>0</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Supply security target</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>50%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
</tr>
<tr>
<td>Biomass potential [EJ/yr]</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Discount rate [%/yr]</td>
<td>12-19</td>
<td>12-19</td>
<td>12-19</td>
<td>12-19</td>
<td>12-19</td>
<td>3-10</td>
<td>3-10</td>
</tr>
<tr>
<td>FCV cost [USD/kW]</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>65</td>
</tr>
</tbody>
</table>

6 Results

Figure 3 shows the use of transport fuels in the eight scenarios for 2050. In the first scenario with no fuel taxes, fuel use in 2050 amounts to 198 EJ. If fuel taxes are considered, fuel use declines to 184
EJ. This is close to the WBCSD result that is 175 EJ for 2050 (WBCSD, 2004). Oil refinery products dominate this scenario (60%) and 30% of them are produced from non-conventional oil. More than half of total transportation fuels (96 EJ) are not derived from conventional oil. Gas-to-liquids and coal-to-liquids play an important role. If a CO₂ incentive is introduced, total fuel use declines by 10%. Coal-to-liquids disappears but gas-to-liquids and ethanol show a significant growth.

The introduction of the regional supply security constraints has only limited impact on a global scale. Methanol and DME grow at the expense of oil products. In case the biomass potential is reduced from 200 to 100 EJ, the use of biofuels declines from 30 to 20 EJ. This is compensated by more oil, methanol/DME and CNG use. In case lower discount rates are applied, total fuel use is reduced to 155 EJ because more capital intensive, fuel efficiency measures are introduced. Under this assumption significant amounts of hydrogen emerge (8 EJ). Low cost assumptions for hydrogen FCVs (last scenario) result in a further increase of the hydrogen share (13 EJ) and a further decline of total fuel use to 150 EJ.

The analysis suggests that conventional oil remains an attractive fuel option, despite government efforts to reduce oil dependency. The introduction of hydrogen requires a combination of CO₂ policies, supply security policies, and low discount rates. The latter can also be seen as an abstract representation of policies to favour vehicles with low emission of local pollutants.

Figure 3: Fuel use in the transport sector, 2050

While CO₂ policies, low discount rate, etc., make hydrogen attractive for e.g., the bus market, large-scale introduction of hydrogen for passenger cars requires both low discount rates and low FCV costs. The results suggest that hydrogen hybrids and hydrogen FCV can co-exist (figure 4). It should be noted that hydrogen consumption in comparison with other fuels does not represent correctly neither the integral number of passenger-kilometres nor the market penetration of hydrogen vehicles because the efficiency of such vehicles is higher and therefore they use less fuel for the same service. In the most optimistic scenario, 30% of all passenger cars are hydrogen fuelled by 2050. An important caveat, however, is that the model does not treat transitional issues in a detailed fashion. Given so-
called “chicken-or-egg” problems, it may be more difficult for new vehicle types to penetrate the market, and to co-exist, than estimated here.

Note that this analysis does not account for modal shift, speed limits or similar behavioural measures that can enhance the energy efficiency. Therefore the energy efficiency potential may be higher than it may seem based on this analysis (IEA, 2004e).

![Figure 4: Hydrogen use in the transport sector, 2050](image)

**Figure 4: Hydrogen use in the transport sector, 2050**

Figure 5 shows the CO₂ emissions from the transport including the fuel production. In the BASE case, emissions increase fourfold. Almost one third of these emissions are from fuel production processes. This growth of upstream emissions represents a major change from the current situation that deserves more attention.

The emissions growth over the period 2000-2050 is 75% in case a CO₂ incentive is introduced. The emissions in 2050 are halved, compared to the BASE scenario. The fact that emissions still grow confirms that reducing emissions in transport is a challenge. Especially, measures on the vehicle side are costly. While emission reduction for vehicles is limited to at most 20%, the main reduction occurs in fuel production processes.

The results suggest that supply security policies, biomass availability, time preferences and technology assumptions for hydrogen FCVs are not so critical for emission reduction as global CO₂ reduction incentive systems are. However, a set of scenarios where these measures are introduced in a different order may show that each of these steps can have important benefits. This needs to be analysed in more detail.

CO₂ capture and storage plays a key role for fuels production processes. Figure 6 shows the total amount of CO₂ that is captured. It ranges from 2.7 to 4.5 Gt of CO₂ per year. For CO₂ capture a key role is played by the IGCC plants that cogenerate electricity and synfuels such as hydrogen and DME. They account for roughly half of total capture. Significant amounts of CO₂ could also be captured from FT-synthesis plants.
Figure 5: CO₂ emissions from the transport sector and from the production of transportation fuels, 2000-2050

Figure 6: CO₂ capture in transportation fuels production, 2050

7 Conclusions
Enhancing supply security and reducing CO₂ emissions is particularly challenging in the transport sector. A number of competing options have been analysed. Our analysis suggests some 60% of all
transportation fuels will still be oil-derived by 2050 but only 40% from conventional oil. Efficiency measures, biofuels but also synfuels from coal and gas, methanol/DME and CNG may have an important role. The fact that a range of options emerge suggests that a future transportation system may differ from the current one. CO₂ capture and storage can be applied in order to reduce emissions in synfuels production. The cost-effective potential for emissions reduction in fuels production is higher in comparison with the reduction potential for vehicles. A key role in this respect is played by the IGCC plant for cogeneration of electricity and hydrogen from coal with CO₂ capture and storage.

The analysis suggests that hydrogen technology will gain significant market share if cost of hydrogen vehicles will be substantially reduced (65 USD/kW) and if environmental and security policies will be implemented. Cost of hydrogen production should also be reduced. It should be noted that hydrogen consumption in comparison with other fuels does not represent adequately the integral number of passenger-kilometres or the market penetration of hydrogen vehicles, because the efficiency of such vehicles is higher and therefore they use less fuel for the same service. Fuel cells are not necessarily needed for a transition to hydrogen fuels as advanced hydrogen ICE or hydrogen hybrid vehicles could provide part of the efficiency and environmental benefits of hydrogen-FCVs. The cost of the vehicle in combination with the relatively low annual use of passenger cars results in high CO₂ emission mitigation costs for any option that increases vehicle cost substantially. However, in the most optimistic scenario, 30% of all passenger cars are hydrogen fuelled by 2050. Public and commercial transport vehicles with high annual use such as buses and trucks can be more attractive niche markets to start the development of a hydrogen fueled transport system. In Western Europe, where three quarters of retail fuel costs are in fact taxes, hydrogen introduction could be facilitated by waiving these taxes during a transition period. A large-scale transition to hydrogen seems unlikely to occur before 2030. Such a transition could be accelerated by policies that reduce investment cost.

A successful hydrogen policy strategy should be flexible so it can make timely corrections to reflect technical progress, consumer needs and social context. It is unlikely that hydrogen and other transport options will develop without strong government intervention and commitments. Achieving significant improvements in the transportation sector will require stable long-term policies to speed up technology development and orient the market towards secure and environmentally benign solutions.

8 References

Risø-R-1517(EN) 257
Session 10 – Wind Energy

Chairman: Ulla Röttger, Amagerforbrænding A/S, Denmark
Wind power plants – status and visions

Poul Sørensen\textsuperscript{1}, Poul Erik Morthorst\textsuperscript{1}, Kenneth Thomsen\textsuperscript{1}, Charles Nielsen\textsuperscript{2}, Jens Carsten Hansen\textsuperscript{1}

\textsuperscript{1}Risø National Laboratory, \textsuperscript{2}ELSAM

Abstract

This paper describes technical and economical challenges related to integration of wind power in power systems. With the increased penetration of large wind power installations in power systems, wind power plays an important role on the economical as well as the technical side of the operation and control of the system. With this increased importance for the system, large wind power installations are often referred to as wind power plants. A vision of revised operation strategies of wind power plants are presented, with the idea to reduce production or stop wind turbines when the electricity price is low and thus save fatigue lifetime to be used later. Then the technical power system demands for integration of wind power are presented. Finally, ELSAMs RETrol vision is presented as a solution model for integration of wind power.

1 Introduction

The limited resources of fossil fuels, combined with a rapid industrial growth especially in developing countries calls for global and sustainable solutions to the energy supply. Wind energy has the potential to contribute significantly to meet this challenge.

Wind energy has developed rapidly the last 30 years. The cost of electrical power produced by wind turbines has decreased steadily while the wind turbine factories have developed from small workshops in the late 1970’ies to the present mature wind power industry. As a consequence of this successful development, wind power has become competitive to other power production technologies in areas with sufficient wind resources.

The development of the modern wind energy technology was initiated in Denmark, and in the first years, the wind energy marked was completely dominated by Danish industry. This development has had a significant, positive influence on the economy and employment in Denmark. As wind energy proved to be competitive among sustainable energy sources, it plays an increasing role on the international level as well. Today, the wind energy industry has matured in Germany, USA and Spain, and other countries, e.g. India show a promising development.

Wind energy also contributes to the security of supply. The European Commission forecasted in the Green Paper 2000 [1] that if the existing trends are to continue then more than 70\% of the EU energy consumption in 2020 will have to be covered by imported energy fuels. The limited resources and the political uncertainties cause an unstable and on the long term growing price for fuel. Wind energy now supplying Denmark with approximately 20 \% of the electricity consumption is an important factor in making the economy less sensitive to fuel prices.

The development of wind energy has also caused more focus on the integration of wind
power into the power system. The main challenges related to large scale integration of wind power are the influence of the wind power on the economic operation of the power system, including the role in deregulated electricity markets, and the more technical influence of the wind power on the stability and the reliability of the power systems, including the possibilities to control wind power.

With the high penetration levels of wind power in the Danish system, wind power installations have become a substantial part of the generation and should be considered as power plants. With a dominating decentralised generation mix like in the Danish power systems, and taking into account the high costs of down regulating the fluctuating wind power, it is also useful to look at wind power at a part of a larger virtual power plant. Modern information technology makes it possible to operate a large number of decentralised power producing plants as a single virtual power plant generating firm power.

This paper describes different aspects of wind power plants. A vision of revised operation strategies of wind turbines and wind farms are presented in section 2, with the idea to reduce production or stop wind turbines when the electricity price is low and thus save fatigue lifetime to be used later. In section 3, the technical power system demands for integration of wind power are presented. Section 4 describes ELSAMs RETrol vision as a solution model for integration of wind power. Finally, conclusions are made in section 5 on the vision of integrating larger scale wind energy in the power systems.

2 Revised operation strategy

The operation of wind power plants is often carried out with focus on maximum production during its design lifetime without any regard to the electricity price. This means that the wind power plants are operated at 100% of the potential power production for a specific wind condition and the basis of this approach is the fixed design lifetime – usually 20 years.

However, the electricity price varies significantly, Figure 1, and a revised control strategy could be based on an assessment of the actual price for a specific operation hour. Thus, if the price of electricity is high, the wind power plant could be operated with a production that corresponds to the full potential (or even higher) and for low prices the wind power plant could be de-rated or stopped.

This revised strategy must be planned in combination with an assessment of the fatigue loading on the wind power plant. The fatigue loads determine the true cost of many of the components of a wind turbine. This means that the actual lifetime of a wind power plant can be increased – without compromising the structural integrity.
The assessment of fatigue load can be done in several ways. The simplest way is to ensure that the wind power plant is operated for exactly the same number of operational hours at a specific loading condition as the design specifications. Thus, if the turbine is designed to operate \( N \) hours in the wind speed range 9-11 m/s, these \( N \) hours can be spend in this wind speed range when the price on the electricity market is above a certain limit. If the number of hours exceeds the design limits for a certain wind speed interval, the turbine is stopped – a situation that only accumulates marginally fatigue damage.

Figure 2 Calculated incomes for a revised operational strategy.

An example is given in Figure 2, where the increase in income is calculated for different revised strategies. The wind conditions and the prices on the electricity market is the 2003 data from the western part of Denmark – repeated year by year – and the reference turbine has a design life time of 15 years. The production price limit is the price, which determines whether the wind power plant should operate at 0% or 100% of the potential production. Since the input time series is 2003 data repeated over and over again, the
extremes of these data are limited (and constant), and it is necessary to specify a
maximum lifetime. In this simple example, no attention is paid to added O&M costs. The
results illustrate that an increased income of 10-20% is possible if the fatigue lifetime is
spend in situations where the electricity price is high.

Other approaches exist for revised operational strategies. It is obvious that the fatigue
lifetime can be redistributed from one load condition to another load condition – if the
net income increases. Such a strategy increases significantly in complexity since the
distribution of fatigue lifetime is very different from one component to another.
Furthermore, the redistribution must be based on cost modelling of the individual
components of a turbine and a possible redesign for an assumed scenario can be
necessary. For a wind farm with several wind turbines, the park control strategy can be
planned with focus on the lifetime consumption of the individual turbines in combination
with the market price of electricity. In this situation the individual turbines can be
operated in a way that ensures an evenly distributed fatigue loading, by up- or down-
rating the turbines in order to change the wake conditions for the downwind turbines –
and thus change the wind condition for the downwind turbines both with respect to
production and loading.

3 Power system demands

The level of wind power penetration in power systems and other characteristics of the
systems such as the export / import transmission capacities are important factors to
determine what is required by the wind turbines to integrate them in the power system.

The influence of the wind power penetration level on the power system is illustrated
quite well by the development in the West Danish power system, which has gone
through a development from almost zero to more than 20 % wind production of the
electricity consumption in less than 30 years.

The limited export transmission capacity is an important limiting factor for integration of
wind power in the Irish power system. Wind power development has just started on
Ireland, but the Irish TSO is very careful to study the influence of wind power in their
system before permission is given to develop new wind power installations.

Grid connection requirements

In the beginning of 1988, the total wind power capacity in the West Danish system
reached 100 MW. This penetration level had relatively little influence on the power
balance and other global issues in the system, which has a minimum load is more than
1000 MW. However, as the wind turbines were concentrated in rural areas where the
grid is relatively weak, the influence of the wind turbines on the local power quality in
those areas became an issue. On this background, the Danish Utilities Research Institute,
DEFU, issued recommendations KR77 [2] for grid connection of wind turbines with the
main focus on the influence of wind turbines and grid strength on the local power
quality.

Eleven years later, i.e. in the beginning of 1999, the installed wind power had increased
to about 1100 MW. This was already a significant penetration level, and moreover the
Danish government planned the development of several large wind farms with the target
of supplying 50 % of the Danish electricity consumption with wind power in 2030.

With such high penetration levels, the wind power production had to be taken into
account on the global system level as well. Therefore, the Danish TSOs were the first to develop a grid code specifically for wind power installations. The first requirements were issued for connection of large wind farms to the transmission system in 1999, and in 2000 a second edition was issued, which is also available in an unofficial English version [3]. The latest versions are from 2004 [4][5], when the installed wind power has increased to almost 2400 MW, and wind energy supplied 23 % of the electricity consumption. The Danish requirements first of all specifies the behaviour of large wind farms and single wind turbines in the event of grid faults, but also provides specifications to the participation in the control of power system voltage and frequency.

According to the Danish Wind Turbine Industry [6], Germany today is leading as wind energy developer with a share of 31 % of the wind turbine market. In Germany, the pattern has been quite similar to the Danish, but a little delayed. In Germany, these requirements to wind turbines are a part of the general requirements to all connections to high voltage and extra high voltage grid [7].

In Ireland, the wind energy development just started. According to Sustainable Energy Ireland [8], the installed wind power capacity was 242 MW in the Republic of Ireland and 51 MW in Northern Ireland in November 2004. For comparison of these figures, the Irish system is quite similar in size to the West Danish system on the demand side.

The target for wind power in Ireland is 500 MW by the end of 2005, and currently more than 2000 MW are in application queue. The combination of very good wind resources and severe power system restrictions makes Ireland a very illustrative and important case.

The main restriction in the Irish power system compared to the West Danish system is the weak interconnection. The only interconnection form the Irish island to Great Britain is the 500 MW DC link from Northern Ireland to Scotland. Moreover, the interconnection between the Republic of Ireland and Northern Ireland is limited to 300 MW AC. Compared to those restrictions, the West Danish system has 1200 MW HVAC transmission capacity to Germany, 1000 MW HVDC to Norway and 600 MW HVDC to Sweden, i.e. totally almost 3000 MW. ESB issued its distribution code [9] in February 2005 with requirements to the same areas as in Denmark, i.e. grid fault behaviour and power control.

In order to provide an internationally agreed reference for the national requirements on power quality, a standard IEC 61400-21 [10] for power quality of wind turbines was issued in 2001. The IEC standard specifies how to measure and assess the power quality of wind turbines, but the requirements are still a national issue, e.g. specified in KR-111 [11]. IEC 61400-21 is currently under revision, with the intension to include the behaviour during grid faults and the participation in voltage and frequency control. This reflects that the fast growth in wind power installed capacity in several power systems has extended the influence of the wind power from local power quality to global system issues such as system reliability and power system control.

**Stability and reliability**

The main concern in the new grid code requirements to wind turbines is the influence of the wind turbines on the power system reliability, because a grid fault in the transmission system could cause simultaneous shut-downs of many wind turbines. Such a simultaneous shut-down of wind turbines would cause a sudden drop of generation in the system, which could cause problems to system stability and thus reliability.
A very challenging test of the ability of wind farms to participate in power system control is to isolate the wind farm on a local grid. A case mentioned in the first Danish specifications and in the Irish distribution code is when a minor subsystem including wind turbines is isolated from the rest of the system.

Also the ability to contribute to black start of the system is important power plant characteristic. In the Irish distribution code this is mentioned, not as a requirement but as something which the TSO should be informed about if it is possible, obviously with the intention to use fully the possibilities in modern, controllable wind turbines and other distributed generators.

**Power control**

The second new area in the Danish and Irish TSO requirements is power control of wind farms. This comprises wind farm active power to support power system frequency as well as wind farm reactive power control to support the system voltages.

Requirements of power control are described detailed in [5]. It involves different types of power control: absolute power limitation, delta limitation, balance control, stop control, ramp limitation, and fast down regulation to support system protection.

Figure 3 shows an example of balance control of the output from the wind farm. At time 100s, the power is ordered down to 60 MW. However, the ramp limitation prevents the power from changing immediately. At time 300s, the power is ordered back to maximum, and again the ramp rate limitation prevents sudden power changes.

![Figure 3. Balance control of wind farm combined with ramp limitation.](image3.png)

Figure 4 shows similar plot for delta control. The advantage of the delta control is that a specified amount (the delta) of reserve power is always available. This can e.g. be utilised in automatic primary frequency control.

![Figure 4. Delta control of wind farm combined with ramp rate limitation.](image4.png)
In the Danish and Irish codes, automatic primary frequency control is required to be implemented in new wind farm and wind turbine controllers. The frequency control should include droop and dead band as shown in Figure 5. In normal operation (without activated balance or delta control), the power setpoint $P_0$ will be equal to the maximum available power $P_{max}$, and the power–frequency characteristics in Figure 5 will only have droop for over-frequencies, because there is no reserve power available for under-frequencies. This overfrequency control is very useful if an area with surplus production is isolated. Then the wind power installations will reduce the power production and support the frequency control in the isolated area and thus prevent it from black-out.

Thus, both primary and secondary frequency control should be supported by wind power plants. The secondary control is intended to respond manually, i.e. relatively slow to small frequency changes, while the primary control should respond automatically and immediately, typically to larger frequency changes e.g. caused by sudden loss of generation in the system.

In the case of sudden loss of generation, the inertia in the power system is also essential to the stability of the system. The inertia limits the rate of change of the frequency $\frac{df}{dt}$ when the generation is out of balance with the demand, and this way it responds even faster than the primary control to sudden loss of generation. The inertia can become critically low in an island system, and also if a smaller area is isolated from the main system. In principle, wind turbines with directly connected generators contribute with their wind turbine rotor inertia to the power system inertia, while the rotor inertia in wind turbines with variable speed is decoupled the power system by the speed controller in the wind turbine. Holdsworth et al [12] proposed an extension of the control of the variable speed wind turbine, which would virtually bring back the inertia of the wind turbine rotor to the power system. In principle, the virtual inertia could be even bigger than the physical wind turbine rotor inertia, but if it is set too big in the controller, the turbine might become unstable because when the speed falls, the aerodynamic torque is reduced.

Reactive power is only required to be controllable to unity power factor in the Danish specifications. However, wind turbines are normally able to provide more advanced grid support. Depending on the technology and the electrical design, wind turbines will normally have some additional capacity for reactive power, although the available reactive power normally depends on the active power as it does for any other generating units in the power system.

The additional reactive power capacity can either be used to control constant reactive power or constant power factor, or it can be used in automatic voltage control. In the latter case, it is essential, that it is the voltage in the wind farm point of common coupling (PCC) which is controlled, and that this is done on the wind farm controller.
level. If the wind turbines are individually attempting to control the voltage in the individual connection points, there is a risk instability and a high flow of reactive power between the wind turbines.

The possible voltage control in the PCC is of course limited by the limited reactive power available in the wind turbines or from other compensation equipment in the wind farm. Reactive power / voltage control can be defined as a combined droop and deadband control is illustrated in Figure 6.

![Figure 6](image)

Figure 6. Specified automatic voltage control with adjustable droop and dead band.

### 3.2 Real wind farm experience

One of the first significant steps in developing controllable wind power plants was the Bockstigen offshore wind farm installed in 1997 connected to the grid on the island Gotland in Sweden [13]. The Bockstigen wind farm is a 2.5 MW wind farm consisting of 500 kW Wind World turbines. The grid in the wind farm connection point in Gotland was very weak at the connection time, and conventional wind turbines would have caused overvoltage problems. To avoid overvoltages and to improve power quality impact in general, the wind farm is controlled by a supervisor, which is able to control the voltage in the connection point. This is first done by controlling the reactive power setpoint in the individual wind turbines. If reactive power control is not enough to avoid overvoltage, energy is dumped in controllable loads installed in the wind turbines. Finally, the supervisor can shut down wind turbines to keep the voltage.

The most significant step in developing wind power plants until now was probably taken with the Horns Rev offshore wind farm in Denmark in 2002 [14]. The Horns Rev wind farm is a 160 MW wind farm consisting of 2MW Vestas wind turbines. Primary control of the frequency is implemented in the individual wind turbines. For secondary frequency control, the wind farm is equipped with a wind farm main controller, which makes it possible to control active and reactive power from a central control room. The Vestas wind turbines in Horns Rev are also able to ride through grid faults as required by the Danish transmission system operators. This minimises the risk for sudden loss of the power produced by the wind farm.

### 4 The REtrol vision

Elsam has composed a sustainable and industrial political aggressive vision for the total Danish energy and transport industries under the title Retrol, where R and E are the initial letters of Renewable Energy.

This vision is the first attempt of connecting the energy and transport industries and creating the necessary conditions for a continued innovative business development in the energy industry. The vision must be seen in the light of Denmark’s strengths within
energy, agriculture, bio-technology and advanced process industry.

The essential notion in the vision is that the central CHP (combined heat and power) plants, which today are the spine of the Danish heat and power supply, are directed towards use of renewable energy and that they are developed for environmental friendly refineries supplying energy, such as power, heat and transportation fuels based on a mix of renewable energy and fossil fuels in accordance with national and international standards. An almost equally important and continuous element in the vision is the fact that it is predominantly based on the leading industrial environments in Denmark, and that it enables continued development of wind turbines in Denmark and increased use of the surplus products from agriculture and forestry. Finally, the vision involves connecting Denmark’s strongest research environments in biotechnology, nanotechnology, energy supply and agriculture.

**Main content of the RETrol vision**

Elsam’s vision for production of RETrol is shown in Figure 7.

![Figure 7. Elsam's vision for the production of RETrol](image)

Concerning output, the RETrol vision means that the power plants produce electricity, heat and liquid fuels such as ethanol and methanol – for use in the transport industry – as direct admixture in petrol, separate use or further manufactured into dimethyl ether (DME) or biodiesel (rape oil methyl ester and rape oil ethyl ester).

Concerning input, surplus products from agriculture and forestry, the organic fraction of refuse and wind turbine power combined with fossil fuels in the form of natural gas and coal are used.

**Production of bioethanol**

The production of bioethanol is one line of the vision. The production of bioethanol on starch, i.e. sugar cane or wheat and corn seeds, is a well-known technology and is practised many places around the world. But basing it on the lignin cellulose part of the plants – the stem or the straw – is the big challenge. Denmark has worked on this challenge for several years at Risø National Laboratory, The Royal Veterinary and Agricultural University of Denmark (KVL) and the Technical University of Denmark (DTU).

Based on the Danish research in this area, the development Novozymes has carried out by, i.e. reducing the price of the enzymes for the process, and Elsam’s work with developing a pre-treatment method (IBUS), Denmark has come a significant step closer to the point, where we can demonstrate a promising bioethanol concept based on straw. The driving force in Europe is EU’s directive on the fact that by 2010 5.75 % of all motor fuel shall be based on biomass.
Firstly, this will of course be done based on grain, but the ambition is that in the long term this will be done based on surplus products, which in many places in the world are considered an expense. Similarly, cut-price grain will be absorbed in the energy industry, which could imply increased agricultural prices for the benefit of industrial countries as well as developing countries.

A very important reason for Elsam to be involved in the development is that we see close synergies between a power plant and a bioethanol plant. The production of bioethanol requires energy, and the power plants have this abundantly and at all levels. Moreover, considerable amounts have been invested in straw handling at numerous power plants and finally, the rest fraction, which cannot be used for the bioethanol production, is burnt in the power plant boiler, unless no other high-value use is found for the product. Though, first it will be examined how much of the rest fraction, which can be used as high value animal feed.

But the development alone does not make bioethanol able to compete with petrol from day one. Therefore, EU has made it possible for the individual countries to tax-exempt bioethanol. This has taken place in Sweden and Germany, while Denmark, as the only country in Europe, has done nothing so far. The Danish position must be reevaluated in 2007 at the latest.

In spite of this, several projects based on grain is today in progress in Denmark. Likewise, Elsam will prepare a basis for decision of a conventional plant – based on wheat – in order to construct the necessary equipment for simultaneous testing of a development line of straw. Furthermore, we will try to obtain EU funding for phase two of the IBUS project.

**Production of methanol**

The production of methanol is the other line of the vision.

The point is to produce methanol at a synthesis from hydrogen, CO and CO2. CO2 is induced by fermentation of ethanol (RE carbon) and separated from the flue gas from the power plants (recycled fossil carbon).

The CO2 is synthesized directly with hydrogen or modified to CO by the use of natural gas. Hydrogen is made by electrolysis based on electricity. Beyond this, non-fermentable parts of the biomass and the waste can be gasificated to CO and hydrogen, which are also applicable in the process.

The main idea is that this process will enable erection of more wind turbines and that power production will cover a share of the production of transportation fuel.

As regards CO2 capture, Elsam participates in a large EU project, which shall identify the best methods of capturing CO2 from flue gas (the CASTOR project).

Methanol processes are a core competence at Haldor Topsøe, who supplies plants and equipments, especially catalysts for methanol production all over the world. Furthermore, Haldor Topsøe is initiator of introducing dimethyl ether (DME) in the transport and energy industries. In this connection, Haldor Topsøe is establishing a plant for methanol and DME production in Iran, among other countries.

**Vision strength**

The strength of the vision is that it is basically founded on renewable energy, it is linking the energy and transport industries, and it builds upon the present Danish competences
and companies.

The vision opens up the possibility of developing a new area of export for large established groups in Denmark (power plants, farms, Novozymes, Haldor Topsoe, wind energy industry and oil and gas companies) as well as smaller Danish companies. It will be necessary with some component development and production aimed at the processing industry, with new components for the car industry and equipment for waste and biomass handling.

The development demands that the Danish research centres and universities are on their toes, delivering results concurrently with the industry demanding the results. Thus, the vision frames the vision for energy, which the Ministry of Science, Technology and Innovation has composed for the energy area in connection with the High Technology Fund.

The vision provides high technological development possibilities within subjects such as new advanced electrolysis, fuel cells, fermentation, pre-treatment of waste and biomass, additives for new fuel mixes, catalysis, gasification of biomass and waste and development of new and cheaper offshore wind turbines.

The condition for the REtrol vision is adjusted market limits. Elsam expects that the energy plan work to be published in the summer of 2005 formulates the necessary framework conditions for the REtrol vision to flourish to the benefit of Denmark.

The success of the REtrol vision is determined by a good and broad cooperation between industry, politicians and research institutes in Denmark. Above all, it is vital that the politicians are in front committing to the vision and thereby creating the framework conditions, necessary for creating the incubator market for the new technologies.

5 Conclusion

Wind energy has developed rapidly the last 30 years. The development is naturally concentrated in areas with good wind resources, and in such areas wind power plays an increased role, not only on the local power quality but also on the more global power system operation and control.

Visions for the further development of the energy systems towards sustainable solutions with a higher penetration of renewable resources and reduced emissions of greenhouse gasses are in the making. One such vision is the REtrol Vision, which a) enables the integration of the energy sub-sectors – power, heating and transport, b) offers opportunities for industrial development, c) and not the least provides new means of improving wind power integration and increasing the renewable energy penetration through sustainable and economically viable hydrogen production serving as a flexible and controllable energy buffer.

The most economical way to operate large scale wind power is not necessarily to produce maximum power at any time. First results of alternative operation strategies indicate that it may be possible to improve the economy by reducing production or stopping wind turbines when the electricity price is low.

On the technical power system side, the increased wind power penetration has caused new requirements to the wind power plants. First of all, the TSOs in many countries have made requirements to the wind turbines ability to stay connected to the grid under and after a grid fault. This fault-ride-through capability is important to avoid a sudden
substantial loss of generation in the power system, which can be very high if the wind
turbines are very sensitive to voltage drops and many wind turbines are installed. It has
become an issue because the capacity of installed wind power has become very high.

Another technical area is the control of frequency and voltage in the system. Wind power
plants replace other power plants, which are responsible for the control in the system.
With more controllability in the wind power plants, it is possible to maintain a safe
system operation with less conventional power plants on-line when wind power
production is high. This is important, because it is costly to keep power plants on-line
with low production.

In view of the growing recognition of the needs for improving sustainability of energy
production, new power system options can be developed. The complexity of such
systems will require clear visions and significant research into solutions across the
various energy sub-sectors as well as development of new technological solutions.
Advantage should be taken of the experience from the Danish power system with a high
wind energy penetration, CHP, and a collaborative environment for research,
development and innovation between public and private stakeholders.

Acknowledgement
This paper is funded by Elkraft System through the PSO 2002 project “Operation and
control of large wind turbines and wind farms” (FU 2102)

References
[4] Vindmøller tilsluttet net med spændinger under 100 kV. Teknisk forskrift for
November 2004.
[5] Vindmøller tilsluttet net med spændinger over 100 kV. Teknisk forskrift for
vindmølleparkers egenskaber og regulering. Elkraft System og Eltra. TF 3.2.5.
December 2004.
meeting. System integration of wind turbines. Dublin, Ireland, November
2004.
and assessment of power quality of grid connected wind turbines. IEC 9 June
2000.


Climate change impacts on wind energy resources in northern Europe

Prof. S.C. Pryor\textsuperscript{1,2} Dr. R.J. Barthelmie\textsuperscript{2} and Dr. E. Kjellström\textsuperscript{3}

\textsuperscript{1}Atmospheric Science Program, Indiana University, Bloomington, IN 47405, USA (spryor@indiana.edu or sara.pryor@risoe.dk).
\textsuperscript{2}Wind Energy Department, Risø National Laboratory, Roskilde, Denmark
\textsuperscript{3}Rossby Centre, SMHI, Norrköping, Sweden

1 Introduction

Energy is a fundamental human need. Heat, light and transport for individuals combined with the needs of industry have created a demand for energy which for the last 100-200 years has been met largely through consumption of fossil fuels leading to altered atmospheric composition and modification of the global climate (IPCC 2001). These effects will be realised on local scales affecting not just temperature and precipitation but also wind, radiation and other parameters. The European Union has an overall target of 12\% of energy (22\% electricity) demand from renewable sources by 2010, as part of a wider strategy to meet its commitment to reduce emissions of greenhouse gases under the Kyoto agreements. In the absence of large-scale development of nuclear energy, this goal can only be achieved by exploitation of renewable energy sources that are competitive in a liberalised energy market. Wind energy is the fastest growing renewable energy source in the European Union. By 2003 more than 28,000 MW of wind energy capacity had been installed in Europe (600 MW offshore). Climate variability and change impact wind energy density and the feasibility of wind energy developments via changes in the atmospheric circulation patterns and hence the wind speed. Since the economics of wind energy depend largely on the site wind speed (power is approximately proportional to the cube of wind speed), there is considerable interest in determining whether future wind climates will continue to resemble those currently experienced.

Evidence for the magnitude of the current inter-annual variability in available wind resources can be obtained by examining the annual wind index computed by EMD (and available from www.emd.dk) for Denmark. This index is a measure of the available wind energy density in a given year relative to the mean for 1987-1998. A value of 100 for any given year indicates that it is an ‘average’ or typical year, values below 100 indicate the wind energy density was below the average for 1987-1998 and a value of above 100 means the wind energy density was above the average for 1987-1998. Even in Denmark, a country noted for its large and stable wind energy resource, the annual values for 1987-1998 vary between a low of 85 and a high of 110, indicating that any given year may have a wind energy power generation potential that is 10\% higher than the average or 15\% lower than the average. The twelve years used for the normalization is relatively short in both a climate context and for the lifetime of a wind farm, and as we move to longer time scales this range (between the minimum and maximum normalized wind energy density) increases. The same is true if we examine wind energy density on a seasonal time scale. Typically in northern Europe highest wind speeds and energy density are experienced during the winter, with lowest wind speeds
and energy density occurring during the summer. The inter-annual variability of winter (December-February, inclusive) wind energy density is even larger than for the annual data. For example, the standard deviation of wintertime energy density 1982-2001 is over 30% of the mean wintertime energy density computed using data from the meteorological station in Copenhagen, while the standard deviation of annual energy density 1982-2001 is 25% of the mean annual energy density. The implication of this summary is that non-stationarities in the climate system can be manifest both as variability and trends in the wind energy resource on timescales relevant to the generation capability of existing and planned wind farms.

In this paper we:

(i) Quantify the impact of climate variability on wind speeds and energy density in northern Europe during the twentieth century.
(ii) Describe tools that may be applied to quantify possible future wind speeds and energy density and the variability of these two parameters.
(iii) Show examples of the application of those tools (from (ii)) to assess likely/possible wind speeds and energy density in northern Europe during the twenty-first century.

2 Historical variability of wind speeds and energy density in northern Europe

Relatively few long-data sets of wind speed observations are available, and because near-surface wind speeds are to some degree localized, our initial research focused on analysis of trends in 850 mb wind speed (approximately 1.5 km above the surface) as manifest in reanalysis data sets. The reanalysis data sets (available from NCEP/NCAR and ECMWF) have a spatial resolution of $2.5 \times 2.5^\circ$ and extend from the 1950’s to date. Analyses of these data indicate the end of the twentieth century was characterized by higher mean wind speeds and energy density than the middle of the century, with the majority of the difference being associated with increases in the upper quartile of the wind speed distribution (highest 25% of the probability distribution) and the winter season. A linear trend fitted to the data indicates the southwest of the Baltic basin experienced an increase in excess of 0.25 m s$^{-1}$/decade for the annual mean. These changes in wind speed are strongly linked to changes in the atmospheric circulation at the scales of weather systems (e.g. mid-latitude cyclones) and beyond (e.g. to large scale teleconnection indices such as the North Atlantic Oscillation which is a measure of pressure gradient from high pressure over the Iberian Peninsula and low pressure over Iceland) (Pryor and Barthelmie 2003). This analysis confirmed our postulate that climate variability is relevant to the assessment and harnessing of wind energy resources and led us to the question: Will projected changes in the global scale climate impact the regional climate of northern Europe sufficiently to cause significant changes in either the magnitude or variability of the annual wind resource?

3 Tools for quantifying possible future changes in wind speeds and energy density in northern Europe

Wind speeds and energy density exhibit variability across a range of spatial and temporal scales, while General Circulation Models (GCM, also known as Global Climate Models) typically generate output at scale of approximately $2 \times 2^\circ$. Hence while initial research directly using output from a GCM suggests that the wind energy density during the twenty-first century (C21st) will be slightly higher in the northeastern Baltic, and slightly lower in the southwest of the Baltic towards the end of the C21st (Pryor et al. 2005b), there is a need to develop more highly spatially resolved projections. The scale reconciliation tools used to undertake this analysis are referred to as ‘downscaling’ techniques and they are designed to
provide more geographically explicit information than is generated using GCM output directly. Downscaling can be undertaken using either:

(i) Physical/dynamical methods, where a numerical model (a Regional Climate Model (RCM)) is used to produce finer resolution fields of the parameter of interest from the large scale description of climate produced by the GCM. That is the GCM provides time-varying descriptions of parameters at the boundaries of the domain over which the RCM is applied (Giorgi and Mearns 1999).

(ii) Statistical/empirical methods, where a transfer function (or functions) is developed that statistically relates the large scale climate parameters generated by the GCM to the near-surface parameter of interest (Wilby and Wigley 1997).

A major difference in these approaches is that:

(i) The former generates:
   - Spatial averages of parameters (at typical scales of 40 x 40 km) across the entire study domain.
   - Realizations for fairly limited time windows due to the large computational cost of undertaking RCM simulations.
   - Projections that are physical consistent with the GCM. The model formulations used in RCM are essentially the same as those used within GCM.

(ii) The latter generates:
   - Site specific parameters but only at locations where a time series of historical data are available to develop the transfer functions.
   - Realizations for extensive time windows and/or multiple scenarios that limited only by availability of GCM output. The computational cost of running these analyses are generally much smaller than for application of a RCM.

4 First analyses of future wind speeds and energy density in northern Europe

4.1 Dynamical downscaling

In this analysis we used the Rossby Centre coupled Regional Climate Model (RCM) (RCAO) (Räisänen et al. 2003; Räisänen et al. 2004) simulations using boundary conditions derived from two GCM: HadAM3H (Pope et al. 2000) and ECHAM4/OPYC3 (Kemball-Cook et al. 2002). Twelve simulations were conducted using RCAO for the domain shown in Figure 1:

- Two GCM sets of boundary conditions: HadAM3H and ECHAM4/OPYC3.
- Two time windows: Control run (January 1, 1961 – December 30, 1990) and the climate change projection period (January 1, 2071 – December 30, 2100).
- Two emission scenarios for the future periods: The two emission scenarios are taken from those developed under the auspices of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2000), and used as foci of the model inter-comparison research presented in the IPCC Third Assessment Report (IPCC 2001). The A2 scenario equates to a moderate to high greenhouse gas cumulative emission for 1990 to 2100 as a result of projected population growth and fairly slow introduction of alternative technologies. This scenario results in global carbon dioxide (CO2) emissions from industry and energy in 2100 that are almost four times the 1900 value and by 2100 emissions from land use change are close to zero, leading to a global CO2 emission in 2100 of almost 28 GtC yr\(^{-1}\). The SRES B2 scenario is based on a medium population projection and results in a global CO2 emission in 2100 of less than half the A2 scenario and hence is associated with lower global warming projections (though there is not a linear relationship between the global temperature increase and CO2 emission totals (IPCC 2001)).
Table 1. Comparison of mean spatial patterns of wind speed and energy density at 10-m for the RCAO simulations derived for the differing boundary conditions (HadAM3H v. ECHAM4/OPYC3) and the control run and the projected climate change simulations (A2 and B2). MAD = mean absolute difference (m s\(^{-1}\)), RMSE = root mean square difference (m s\(^{-1}\)). Also shown are the comparisons of the control run simulations with the NCEP/NCAR Reanalysis (NNR) data (the RCAO output was aggregated to the NNR grid cells).

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Wind speed</th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAD</td>
<td>RMSE</td>
</tr>
<tr>
<td>Comparison for historical climate: 1961-1990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCAO with HadAM3H boundary conditions v. NNR</td>
<td>0.24</td>
<td>0.72</td>
</tr>
<tr>
<td>RCAO with ECHAM4/OPYC3 boundary conditions v. NNR</td>
<td>0.30</td>
<td>0.78</td>
</tr>
<tr>
<td>RCAO with ECHAM4/OPYC3 boundary conditions v. RCAO with HadAM3H boundary conditions</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAD</td>
<td>RMSE</td>
</tr>
<tr>
<td>RCAO with ECHAM4/OPYC3 boundary conditions: Control v. A2</td>
<td>0.30</td>
<td>0.34</td>
</tr>
<tr>
<td>RCAO with ECHAM4/OPYC3 boundary conditions: Control v. B2</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>RCAO with HadAM3 boundary conditions: Control v. A2</td>
<td>0.00</td>
<td>0.06</td>
</tr>
<tr>
<td>RCAO with HadAM3 boundary conditions: Control v. B2</td>
<td>0.01</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Comparison for projections from 2 GCM

<table>
<thead>
<tr>
<th>A2 scenario: RCAO with ECHAM4/OPYC3 boundary conditions v RCAO with HadAM3 boundary conditions</th>
<th>Wind speed</th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAD</td>
<td>RMSE</td>
</tr>
<tr>
<td>0.25</td>
<td>0.28</td>
<td>28.66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B2 scenario: RCAO with ECHAM4/OPYC3 boundary conditions v RCAO with HadAM3 boundary conditions</th>
<th>Wind speed</th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>0.19</td>
<td>17.74</td>
</tr>
</tbody>
</table>

The twelve RCAO simulations were examined to determine if there are substantial differences between near-surface wind speed and energy density calculated for the control run versus the climate change projection period for either of the two emission scenarios or simulations conducted using boundary conditions from the two GCM. On an annual basis the differences in the mean wind speed and energy density computed for the climate change projection periods relative to the control run (1961-1990) are of similar magnitude to...
differences in the RCAO control simulations using differing boundary conditions and to differences between the RCAO control runs and the reanalysis data from NCEP/NCAR (NNR) (Table 1). Simulations conducted using boundary conditions from ECHAM4/OPYC3 indicate much larger changes in the projected climate change simulations relative to the control period than are manifest in the simulations conducted using the HadAM3H boundary conditions. The spatial manifestations and magnitude of possible changes in wind energy potential thus remain uncertain. Due to the high inter-annual variability in energy density and offsets of relative energy density in the control runs for the two different sets of boundary conditions (Pryor and Barthelmie 2004; Pryor et al. 2005a), at this point it seems prudent to assert that the analyses do not indicate statistically significant (robust) changes in the wind climate of 2071-2100 relative to 1961-1990 for both the A2 and B2 emission scenarios.

4.2 Empirical downscaling

Multiple empirical downscaling techniques have been applied to downscale different surface parameters. The approach we have developed for application to wind energy applications is unique in a number of ways:

(i) It is specifically tailored to analysis of wind speeds. It generates the Weibull parameters of the wind speed probability distribution. This distribution is commonly used to represent wind speeds and hence these parameters are commonly used in the wind energy community to compute energy density.

(ii) It avoids difficulties in reproducing the time structure of geophysical parameters by focusing instead on the probability distribution of the wind speed rather than its time sequence.

(iii) It avoids a focus on mean wind speeds. Energy density is related to the cube of the wind speed and hence is more sensitive to changes in the upper percentiles of the probability distribution. This effect is even more pronounced when considering the fraction of the energy density that can be harnessed. Many wind turbines have cut-in wind speeds of the order of 4 m s\(^{-1}\), so wind speeds below that level are below the operating range of the turbine and thus do not contribute to the wind energy that may be harnessed for electricity generation.

In brief, in this technique the mean and standard deviation of relative vorticity (a measure of the rotation at the synoptic scale which is related to vertical motion and hence the draw down of momentum from higher levels in the atmosphere) at 500 hPa and mean sea-level pressure gradients (a measure directly related to the near-surface forcing of wind speeds) computed from GCM are the predictors, and parameters of the wind speed probability distribution at surface stations are the predictands. The two parameter Weibull probability density function is used to represent the wind speed probability distribution:

\[
p(U) = \frac{k}{A} \left( \frac{U}{A} \right)^{k-1} \exp \left[ -\left( \frac{U}{A} \right)^k \right]
\]

for \( U \geq 0, A > 0, k > 0 \)  

where \( k \) is a dimensionless shape parameter (a measure of the peakedness of the distribution), \( A \) is the scale parameter (a measure of the central tendency), \( U \) is the time series of wind speed observations, and \( p(U) \) is the probability density function.

Once the \( A \) and \( k \) parameters are known moments and percentiles of the wind speed distribution may be computed, as can the energy density (\( E \)):

\[
E = \frac{1}{2} \rho A^3 \Gamma \left( 1 + \frac{3}{k} \right)
\]
where $\Gamma$ is the incomplete gamma function and $\rho$ is air density.

Our downscaling methodology is based on multiple linear regression, in which the monthly station-specific Weibull parameters (computed from the observed data) are the predictands and the means and standard deviations of AOGCM-derived relative vorticity and mean sea-level pressure gradients during part of the conditioning period are the predictors. Once the regression equations have been conditioned they can then be applied to any other data set of predictors. Bootstrap resampling of the time series of the predictors is used to assess whether the distributions of relative vorticity at 500 hPa and sea-level pressure gradients are influenced by stochastic effects and whether these substantially bias the downscaling of the Weibull parameters at each downscaling site (Pryor et al. 2005c) (see Figure 1 for the sites used in this analysis).

An example of the results of empirical downscaling conducted for the Copenhagen site for five different GCMs is shown in Table 2. As shown, the results from the five GCM for 1961-1990 closely approximate the observation based estimate for 1982-2001. As also shown, although the models show slight decreases in average energy density in 2046-2065 relative to 1961-1990, the change is small and is within the uncertainty of the technique and the range of realizations for the five GCM. Hence this analysis implies that at least for Copenhagen there is no evident for a statistically significant change in the energy density between 1961-1990 and 2046-2065 for the A2 emission scenario.

Table 2. Comparison of empirically downscaled energy density for 10-m at Copenhagen using downscaling of data from five GCM. The first number listed for each GCM and time period is the best estimate of the energy density, the values given in parentheses show the uncertainty bounds computed from the bootstrapping analyses). The energy density during 1982-2001 computed from wind speeds observed at 2-m and extrapolated to 10-m using the power law is 317.4 W m$^{-2}$.

<table>
<thead>
<tr>
<th>Model</th>
<th>Downscaled energy density (1961-1990)</th>
<th>Downscaled energy density (2046-2065, A2 emission scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFDL CM2.0 Geophysical Fluid Dynamics Laboratory, NOAA, USA</td>
<td>334.6 (326-343)</td>
<td>327.8 (318-336)</td>
</tr>
<tr>
<td>GISS ModelE-R Goddard Institute for Space Science, NASA, USA</td>
<td>332.8 (312-341)</td>
<td>316.7 (296-335)</td>
</tr>
<tr>
<td>IPSL CM4 V1 Institute Pierre Simon LaPlace, France</td>
<td>334.4 (321-354)</td>
<td>315.1 (305-326)</td>
</tr>
<tr>
<td>MIROC3.2 medium resolution Center for Climate System Research, University of Tokyo, Frontier Research Center for Global Change, Japan</td>
<td>334.2 (324-345)</td>
<td>310.0 (295-325)</td>
</tr>
<tr>
<td>MRI_CGCM2.3.2a Meteorological Research Institute of Japan</td>
<td>322.8 (315-332)</td>
<td>311.5 (301-322)</td>
</tr>
</tbody>
</table>

5 Concluding remarks

Annual mean wind speeds and wind energy density over northern Europe were significantly higher at the end of twentieth century than during the middle portion of that century, with the majority of the change being focused on the winter season. To address questions regarding possible future wind climates we employ dynamical and empirical downscaling techniques that seek to take coarse resolution output from General Circulation Models (GCM), run to provide scenarios of future climate, and develop higher resolution regional wind climates. Analyses of the wind climate during the historical record indicate that both the dynamical approach (using the RCAO) and the empirical approach (using our probabilistic approach)
are capable of generating accurate, robust and quantitative assessments of the wind climate and energy density in northern Europe, and hence that they may be of great utility to those seeking financing for, or risk management of, wind farms in the face of climate uncertainty. The synthesis of application of these downscaling tools to climate projections for northern Europe is that there is no evidence of major changes in the wind energy resource. However, more research is required to quantify the uncertainties in developing these projections and to reduce those uncertainties. Further work should also be conducted to assess the validity of these downscaling approaches in other geographical locations.

6 Acknowledgements

We gratefully acknowledge the international climate modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.

Limited financial support for this research was provided by ‘Impacts of Climate Change on Renewable Energy Sources and their Role in the Energy System: 2003-2006’ project funded by the Nordic Energy Research. The computational component of the research was made possible by the following grants to Indiana University from IBM, Inc. (Shared University Research) and the National Science Foundation (grant # 0116050).

7 References


Pryor S.C., Barthelmie R.J., Kjellström E.: 2005a, 'Analyses of the potential climate change impact on wind energy resources in northern Europe using output from a Regional Climate Model', Climate Dynamics In review.

Pryor S.C., Schoof J.T., Barthelmie R.J.: 2005c, 'Potential climate change impacts on wind speeds and wind energy density in northern Europe: Results from empirical downscaling of multiple AOGCMs', *Climate Research* **In review**.


Is least cost wind power always local in Europe?

A balancing act between more transmission and lower load factor

Gregor Giebel, Morten Nielsen,
Risø National Laboratory
Tel +45 4677 5095, Gregor.Giebel@risoe.dk
Brian Hurley, Airtricity,
Ravenscourt Office Park, Sandyford, Dublin 18, Ireland

On- and offshore wind power development has taken on the forms of big business. Wind power in the age of well over 30$/barrel oil is at the best sites in Europe already fully competitive with new conventional generation. However, the available resources are exploited differently in different countries - some countries have a favourable political climate for wind power, but not necessarily the best wind climate, and still attract the largest investments in wind power. This paper analyses the options to provide wind power to selected load centres in Europe, looking at the production cost of the kWh at the production site, and includes realistic transmission cost to provide kWhs at the demand site. The resource is estimated from global wind power data based on NCEP Reanalysis and from previous wind resource studies, the financial data is from experience. Installation cost are calculated differently for on- and offshore installations. The result of this study is open yet, but we expect to shed some light on the question whether it might be more cost-effective to build more transmission for wind power than to try to exploit it yourself at mediocre sites - a trend which is even continuing with larger penetration, since the best sites are already gone.

1 Introduction

This paper is heavily modelled after the paper presented by us in the EWEC 2004 in London [1]. Let me summarise here some of the key messages from this paper:

The wind resource available in Europe on land and offshore is easily enough to provide the current target of Greenpeace and EWEA [2] of providing 12% of wind energy in Europe. Actually, the resource would allow to cover the total European electricity demand by wind energy alone, using the wide areas in the North Sea. The wide distribution of wind power would also firm up the resource (transport issues notwithstanding) due to the fact that wind power is correlated on a scale of about 700 km, which means that wind power from a large area is fairly smooth. Also, wind power offshore has less diurnal and yearly variation than wind power onshore. The smoothing effect has been shown in the previous paper using the reanalysis derived generation profiles from 6 offshore sites (Thames Estuary, Baltic Sea, Orkney, Celtic Sea, Trafalgar, Mediterranean (Marseilles)). “With all wind capacity installed at one location, the frequency of no wind production is around 13%. Periods of full load are also quite frequent, occurring approximately 30% of the time. The distribution of load
factors has two peaks; one at full load and the other at zero load. This is to be expected, considering the shape of a turbine power curve. This pattern is reflected at all [single] locations [...]. As capacity is added [distributed] successively to each location, the probability of no wind production falls to zero. The distribution of load factors takes on a more Gaussian shape; with just one peak around 55% load factor. The majority of production is clustered around the median value with 2/3 of all load factors between 30-70% of total capacity.” Also the observed changes in power output over 6 hours were mostly below 10% of the installed generation for the well-distributed case.

In this paper, we want to have a closer look at the financial impact of putting wind farms where the wind is good, and compare this to the higher transmission cost this incurs. Is there a “rule of thumb” for when a wind farm should be built close to the consumer or closer to high wind speeds? And how can the political support system be tailored to achieve the goals? Which are those, anyway?

2 The Balancing Act

In the last years, the installation of wind power in Europe has advanced by leaps and bounds. However, while the wind resource is greatest in the north-west of Europe (the British Isles and any part of Europe with a westerly shore), most of the installation was in Denmark (fairly windy), Germany (windy in parts) and Spain (with a few really windy locations). This is due to the fact that the political climate for wind energy was traditionally better in these countries than for instance in the UK. In the end of 2004, the Republic of Ireland had 339 MW installed, the UK a disappointing 888 MW, but Germany had 16 629 MW, Denmark 3 117 MW and Spain 8 263 MW installed [3]. The current plans for offshore use seems to straighten out this imbalance somewhat, but Germany remains the clear leader with announcements of about 50 GW of capacity installed offshore (though next to nothing has been installed yet), while the UK has over 1700 MW in various stages of planning, being built or already operating.

The system or state has some goals: the security of supply is one, both in the short term (no power outages) and long term (using fuels available for a longer period in the future). Also, a good environment with a corresponding low output of climate and noxious gases is a goal, as well as the least cost of electricity for industry and consumers alike. The state (be it the nation state or the intergovernmental European Union) has the market rules at its disposal to influence the best combination of fulfilling these goals.

There are two sides to the installation success: the support scheme in place and the ease of the planning process. In the three onshore leaders, both were in place. In the UK, the planning process onshore delayed many wind farms for years, leading at some stage to more than 2 GW of projects being stuck in the planning pipeline. Offshore, the permitting process is easier, which explains the quick expansion of offshore wind in the UK. In Denmark, the change of government in 2002 reversed the support scheme, which led to a sharp drop in new installations. In Germany, the situation onshore is characterised by a lack of areas in good wind conditions, as the windiest sites near the coast are already taken. The problem illustrated here is that wind power, due to the purely national nature of the support schemes, gets built at technically sub-optimal sites. In the following, we want to show therefore what the solution could look like with a fully European access and support scheme in place.
Under the assumption of a supra-national extension of support schemes, the question can be posed whether it is better to build wind power at mediocre sites, or to go further away to high-wind places and bear the additional transmission cost. To investigate this optimisation problem, we will introduce in the following a financial model and populate it with real-life data.

### 2.1 Capital Cost of Wind farms

For onshore wind farms, the range of costs are taken from fig.2.3 p. 99 in the EWEA publication [4]. These range from 900 euro to 1,150 euro per kW installed, including grid connection. For the purposes of this analysis, the figure of 1000 euro is used. For offshore a cost of 1500 euro per kW installed is used.

### 2.2 Cost Estimates for New Grid Elements

The cost of transmission has been estimated assuming the use of DC technology. For power levels of 500MW+ and distances of 100km+ this is the only viable technology. Due to the absence of a synchronous source, it has been assumed that it would be necessary to use voltage source converters at the wind farm end. Although to date this technology has not been used at these power levels, there are no obvious technical reasons why this could not be done [5,6]. At the load end, conventional converter technology would be employed with transmission voltages in the region of +/- 450kV.

Costs have been estimated using averages of several internal and external sources including the above reference. Capital costs and losses split between fixed costs (/MW) and variable costs (/MWkm) have been assumed as follows:

<table>
<thead>
<tr>
<th></th>
<th>Capital costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>Fixed cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost (€m/MW)</td>
<td>0.378</td>
<td></td>
</tr>
<tr>
<td>Offshore cost (€/MWkm)</td>
<td>630</td>
<td></td>
</tr>
<tr>
<td>Onshore cost (€/MWkm)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>DC</td>
</tr>
<tr>
<td>Fixed cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>%/100km</td>
<td></td>
<td>0.33%</td>
</tr>
</tbody>
</table>

**Table 1 Capital Costs**

It has been assumed that annualised costs are equivalent to 10% of capital costs. This results in transmission costs excluding losses ranging from under €0.02/kWh to around €0.06/kWh, as distances range from 500km to 3000km and depending on the offshore/onshore balance. This compares with average costs paid for grid capacity of €0.006/kWh from England to France and €0.019/kWh from Germany to the Netherlands in 2003.
Whilst there is likely to be a charge for connecting to the AC grid at the load end, this may be a negative charge if the wind farm output has, as is assumed above, been transported to a major load centre. Therefore a zero charge has been assumed here as a conservative assumption.

3 Results

A number of production cases with widely varying wind resource has been used here. While the amount of equivalent Full Load Hours (FLH) depends on the type of turbine and the shape of the wind speed distribution, the most important factor is the mean wind speed. The number of FLH ranges from just below 1600 hours for the low wind area onshore, to over 2600 FLH for the onshore high-wind area. Offshore, the wind resource is often even better, like in the case of the assumed 10 m/s case in North Sea South with over 3600 FLH, or the planned Greater Gabbard wind farm in the Thames Estuary with 3200 FLH. For comparison, two very high wind onshore cases south of Europe have been taken into account (already presented in a previous paper at the predecessor to this conference [7]). In southern Morocco or the Western Sahara, where the wind gains momentum over 4000 km of Atlantic Ocean, and where the coastline is not everywhere densely populated, high and steady wind speeds allow for 4000 FLH. Local effects of channelling and thermally driven winds make the Gulf of El Zayt, along the Egyptian Red Sea coast, probably the best wind power site in the world, with up to 6000 FLH. Since the financial model divides the installation cost by the number of FLHs, the very high capacity factor site in Egypt is doing well despite the very long line to Athens (the closest major point of consumption in Europe).

<table>
<thead>
<tr>
<th>TRANSMISSION CASES</th>
<th>Distance</th>
<th>Offshore</th>
<th>Total</th>
<th>Total capital costs (€m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Onshore Km</td>
<td>Offshore Km</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Scotland to Dublin</td>
<td>175</td>
<td>55</td>
<td>230</td>
<td>448</td>
</tr>
<tr>
<td>Dublin to French Alps</td>
<td>1355</td>
<td>45</td>
<td>1400</td>
<td>678</td>
</tr>
<tr>
<td>NW Africa to Spain</td>
<td>1500</td>
<td>30</td>
<td>1530</td>
<td>697</td>
</tr>
<tr>
<td>N Norway to Mid Germany</td>
<td>500</td>
<td>1500</td>
<td>2000</td>
<td>1424</td>
</tr>
<tr>
<td>NW Russia to Mid Germany</td>
<td>2000</td>
<td>0</td>
<td>2000</td>
<td>778</td>
</tr>
<tr>
<td>Greater Gabbard to Köln</td>
<td>290</td>
<td>160</td>
<td>450</td>
<td>537</td>
</tr>
<tr>
<td>Baltic to Mid Germany</td>
<td>200</td>
<td>200</td>
<td>400</td>
<td>544</td>
</tr>
<tr>
<td>Greater Gabbard to Netherlands</td>
<td>50</td>
<td>200</td>
<td>250</td>
<td>514</td>
</tr>
<tr>
<td>South Irish Sea to Köln</td>
<td>800</td>
<td>240</td>
<td>1040</td>
<td>689</td>
</tr>
<tr>
<td>North Sea North to Mid Germany</td>
<td>300</td>
<td>500</td>
<td>800</td>
<td>753</td>
</tr>
<tr>
<td>North Sea South to Mid Germany</td>
<td>350</td>
<td>250</td>
<td>600</td>
<td>606</td>
</tr>
<tr>
<td>Irish Sea to France</td>
<td>1</td>
<td>500</td>
<td>501</td>
<td>693</td>
</tr>
<tr>
<td>Celtic Sea to Mid Spain</td>
<td>300</td>
<td>1000</td>
<td>1300</td>
<td>1068</td>
</tr>
<tr>
<td>Gulf of El Zayt to Athens</td>
<td>500</td>
<td>2000</td>
<td>2500</td>
<td>1738</td>
</tr>
</tbody>
</table>

Table 2 Transmission cases
To calculate the cost of transmission of a MWh from a wind farm to a load centre, the utilisation factor of the wind farm was set equal to the capacity factor of the wind farm. This is a worse case assumption, as the likely utilisation factor of parts if not all of the transmission line could be much higher as other power could also be transmitted. The capital cost of production per MWh at the wind farm site is calculated using a capacity factor derived from the estimated wind speed at the site.

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind speed m/s</th>
<th>Capital cost generation per MWh</th>
<th>Capital cost transmission per MWh</th>
<th>Total capital cost at load centres per MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Wind Area (Onshore)</td>
<td>7.07m/s at 60m*</td>
<td>379</td>
<td>0</td>
<td>379</td>
</tr>
<tr>
<td>Medium wind area (Onshore)</td>
<td>6.45m/s at 60m*</td>
<td>450</td>
<td>0</td>
<td>450</td>
</tr>
<tr>
<td>Low wind area (Onshore)</td>
<td>5.5 m/s at 60m*</td>
<td>633</td>
<td>0</td>
<td>633</td>
</tr>
<tr>
<td>Egypt to Athens</td>
<td>11.5 m/s at 40m</td>
<td>167</td>
<td>289</td>
<td>456</td>
</tr>
<tr>
<td>NW Africa to Spain</td>
<td>9.25 m/s at 40m</td>
<td>250</td>
<td>170</td>
<td>420</td>
</tr>
<tr>
<td>South Irish Sea to French coast</td>
<td>8.5m/s at 100m</td>
<td>512</td>
<td>237</td>
<td>749</td>
</tr>
<tr>
<td>South Irish Sea to French coast</td>
<td>10m/s at 100m</td>
<td>414</td>
<td>192</td>
<td>606</td>
</tr>
<tr>
<td>North Sea South to Germany</td>
<td>8.5m/s at 100m</td>
<td>510</td>
<td>206</td>
<td>716</td>
</tr>
<tr>
<td>North Sea South to Germany</td>
<td>10m/s at 100m</td>
<td>413</td>
<td>167</td>
<td>580</td>
</tr>
<tr>
<td>North Sea North to Mid Germany</td>
<td>&gt;10m/s at 100m</td>
<td>&lt;413</td>
<td>&lt;167</td>
<td>&lt;580</td>
</tr>
<tr>
<td>Baltic Sea to Mid Germany</td>
<td>8.5m/s at 100m</td>
<td>510</td>
<td>185</td>
<td>695</td>
</tr>
<tr>
<td>Baltic Sea to Mid Germany</td>
<td>10m/s at 100m</td>
<td>419</td>
<td>210</td>
<td>629</td>
</tr>
<tr>
<td>Thames Estuary to Netherlands</td>
<td>~9m/s at 100m</td>
<td>467</td>
<td>160</td>
<td>627</td>
</tr>
</tbody>
</table>

* Adjusted from 50m with Log Law r=0.3

Table 3 Total capital costs at load centres per MWh

The results show that good onshore sites in Europe are hard to beat. Have in mind that this table only includes the investment needed to exploit the resource - the operations and maintenance cost of the transmission line and the wind farm are not explicitly modeled. Often though this can be modeled as a percentage of the total investment, and while the percentage for the wind farm will be different from the one of the transmission line, both will be relatively small, only a few percent per year.

While the best sites are clearly high-wind onshore sites, both cases in northern Africa can provide power at an investment cost including transmission similar to a medium site onshore. However, there are two further considerations: near these sites, electricity use is increasing rapidly, therefore most of the produced wind power can be used locally. Also, getting a pan-European market agreement in place is difficult, and integrating outsiders probably even more so.
4 Conclusions for Europe

What emerges from examination of the table above through ranking the cases on the basis of the delivered capital cost of the electricity per MWh, is that after medium to high wind speed areas of Europe are no longer available, it is more economic to facilitate development in high wind areas on land such as in the UK, Ireland and offshore in the North Sea and Irish Sea. Some specific high-wind areas in Africa could also be used, but exploitation of these in the near term for European electricity consumption seems unrealistic. To facilitate this development, it would be necessary to plan for extensive new transmission in the North Sea, and also between Ireland and the UK to avail of this secure source of electricity.

5 A Project for Europe: The European Super Grid

*Figure 1: The European Super Grid for Wind Power. Idea Paul Dowling, Airtricity.*
6 References


2 Greenpeace: *Sea Wind Europe*. Study, 2004

3 www.EWEA.org


5 PB Power, *ETSU Concept study - Western Offshore Transmission Grid*, February 2002

6 Hughes, P: The benefits of Europe-wide offshore wind power deployment and Interconnection, Nov. 2004

7 Giebel, G., N.G. Mortensen, G. Czisch: *Effects of large-scale distribution of wind energy in and around Europe*. Risø international energy conference, Risø (DK), 19-21 May 2003
Session 11 – Distributed Energy Systems

Chairman: Hans Jørgen Rasmusen, DONG, Denmark
Distributed generation for sustainable development – Case Finland

Research Manager Satu Helynen
VTT Processes
P.O.Box 1603
40101 Jyväskylä
Finland
Tel. +358 20 722 2661
Satu.Helynen@vtt.fi

Abstract

During 1980’s CHP production increased rapidly because the production of forest industry was growing fast and district heating networks were enlarged. Electricity prices were moderate because of large capacity additions using nuclear power. The competitiveness of CHP plants using solid fuel needed a minimum heat load of 200-300 GWh/a, which meant about 30 MW electricity. Natural gas fired CHP plants were competitive when annual heat loads were over 50 GWh. In the 1980’s power plant investments, price of energy, and imports of fuels and electricity were regulated. Also most of the largest energy companies were owned by the state. Privatisation and deregulation started in the 1990’s; deregulation of the electricity market was completed in 1996. In 1990’s the smallest solid fuel CHPs were providing 5 MW electricity, the economy was guaranteed by investment subsidies up to the level of 30 %. Presently the competitiveness level has decreased to 1 – 3 MW electricity, and novel technologies with higher power-to-heat ratios have been developed. Kokemäki CHP plant, having start-up in 2005, with a fixed bed gasifier for wood fuels connected combustion engines is presented, as well as other new demonstrated concepts. Both technical, economical and institutional issues on distributed generation and its connection to transmission and distribution networks of electricity, district heat and natural gas are described. The role of distributed generation in the deregulated energy market and the emission trade is discussed.
1 Introduction

In Finland, energy consumption per capita is high due to the severe climate, long distances and energy-intensive basic industry. Industry consumes over 50% of the total energy demand, and space heating 19%. Self-sufficiency in energy supply is in Finland less than 50%, because all the fossil fuels and also up to 15% of electricity are imported to Finland. The gross efficiency of combustible fuel based electricity generation is exceptionally high (65%), because one third of power generation is covered by cogeneration plants (Fig. 1). Half of those plants produce power and district heat for municipalities and and the other half operate in the industry producing power and process steam.

The utilisation of local renewable energy sources for heat and electricity production is promoted by the Finnish energy strategy in order to reduce greenhouse gas emissions and to increase security of the energy supply (MTI 2001). Also positive effects on employment and economy of rural areas are significant.

![Figure 1. Electricity production in Finland (Kara 2004).](image)

Bioenergy covers in Finland 20% of the primary energy consumption and 10% of the electricity demand which are the highest figures within the industrialised countries. Possibilities to increase the total use of bioenergy by 50% and nearly to double the generation of bioelectricity before 2015 has been identified by VTT Processes (MTI 2000).

Biomass-based fuels have traditionally included residues from the chemical and mechanical forest industry and wood fuels used for heating homes. Forest chips from harvesting residues, straw, perennial energy crops, such as reed canary grass, biogas and recycled fuels have complemented the supply of biomass-based fuels during the last decade. Multifuel operation of boilers and cofiring biomass with coal are preferred in large power plants because the availability of many types of biomass is seasonal and can have significant variations from year to year.
2 Role of combined heat and power (CHP) production in Finland

2.1 Increased competitiveness of CHP

The major source of distributed energy generation in Finland is combined heat and power (CHP) production that typically decreases about 30% of the fuel demand compared to separated heat generation by boilers and power generation by condensing power plants. The share of CHP of the total electricity consumption was 32% in 2004, and the share has increased steadily (Fig. 2).

During the late 1980’s CHP production increased rapidly because the production of forest industry was growing fast and district heating networks were enlarged. Electricity prices were moderate because of large capacity additions using nuclear power. The competitiveness of CHP plants using solid fuel needed a minimum heat load of 200-300 GWh/a, which meant about 30 MW electricity. Natural gas fired CHP plants were competitive when annual heat loads were over 50 GWh. In the 1980’s power plant investments, price of energy, and imports of fuels and electricity were regulated. Also most of the largest energy companies were owned by the state.

Privatisation and deregulation started in the 1990’s; deregulation of the electricity market was completed in 1996. In 1990’s the smallest solid fuel CHPs were providing 5 MW electricity, the economy was guaranteed by investment subsidies up to the level of 30% (MTI 2003).

Presently the competitiveness level has decreased to 1 – 3 MW electricity when using solid fuel, such as wood chips (Fig. 3).

Figure 2. The share of CHP in the total electricity generation in Finland (Kara 2004).
Combined heat and power (CHP) production in the forest products industry and district heating networks of municipalities based on fluidised bed boilers and steam turbines is still the dominant technology for bioenergy utilisation in Finland. Power-to-heat ratio has improved with higher steam values, and supercritical once-through circulating fluidised bed boilers using also biomass as a cofiring fuel with coal are under design.

### 2.2 Possibilities to increase CHP

The available heat loads for CHP are smaller and smaller, because larger, most competitive heat loads have already been utilised. The share of district heating has increased steadily replacing especially use of fuel oil for heating (Fig. 4) providing heat load also for CHP. Another favoured option to replace exported fuels is the use of wood fuels in farms, homes and separate buildings, especially heating systems for wood chips and pellets have been installed widely during the last years.
Process industry can provide a high number of annual operating hours for CHP plants which improves economy. Mechanical wood processing, such as saw mills, has both wood residues for fuel and heat demand for drying purposes, which creates favourable conditions for CHP.

3 New technologies

The fluidised bed combustion is dominant for large-scale applications of bioenergy worldwide, and the market leaders of those technologies are operating in Finland. About 100 large-scale cogeneration units (district or process heat 10-500 MWth, electricity 5-250 MWe) are operating with fluidised bed boilers and steam turbines in Finland. Smaller units (0.5- 5 MWe) use typically grate boilers (Figure 5).

![Figure 5. Modular CHP plants with rotating grates 1 – 4.5 MWe power + district heating (Wärtsilä Biopower).](image)

Fixed and fluidised bed gasifiers using wood chips have been applied for heat generation since 1980’s. The implementation of product gas cleaning enables the use of gas engines or turbines for electricity generation with a high power-to-heat ratio. The Kokemäki demonstration plant is under construction (Fig.6) by Condens Oy. Its technological innovations are connected novel tar reforming and gas filtering which reduce the demand of product gas scrubbing considerably. Test facilities at VTT in Espoo include 0.6 MW gasifier pilot plant with catalytic gas cleaning, gas filtration and scrubber, pilot boiler with flue gas cleaning equipment and special gas burner as well as laboratory and bench-scale test rigs for gas cleaning R&D. The investment cost for the 1.8 MW electricity and 4.3 MW district heat demonstration plant is 4.5 million euros.
The future target is CHP plants for ever-smaller heat consumers, because the available large heat loads for district and industrial process heating in Finland are already utilised for combined heat and power consumption (Fig 7.). Diesel and steam engines, and steam and gas turbines are now applied in small-scale CHP of 200 kW - 3 MW electricity. Microturbines, fuel cells, Organic Rankine Cycle (ORC) and Stirling engines are future options for smaller capacity classes.

All these new options need standardised concepts and mass or serial production to obtain competitiveness without significant subsidies or other promotion measures. The serial production of CHP plants could be a major measure to decrease investment costs in lowest capacity classes. Earlier steam boilers and turbine plants with all auxiliary systems and buildings have been tailored plant by plant which increases planning and
project management cost significantly. In the same, possibilities to reduce material and manufacturing costs are not fully utilised. Wärtsilä has reported that costs could be reduced by more than 40% if plants have advanced serial production (Fig. 8).

![Relative Costs, %](image)

**Figure 8. Possibilities for cost reduction of small CHP plants (2 and 5 MWe) using serial production (Wärtsilä Biopower).**

The further targets of development of CHP in Finland are summarised in the Figure 9.

![Targets of Development of CHP in Finland](image)

**Figure 8. Targets of the development of CHP in Finland (Kara 2001).**
4 Conclusions

The main option for Finland to increase the efficiency of power generation has been the switch from condensing power plants to combined heat and power production (CHP). CHP plants today produce already over 35% of the total electricity supply in Finland, but the feasible goal could be about 50% in 2030. About 75% of district heat is provided from cogeneration plants with a typical overall annual efficiency of 85-90%.

CHP is an efficient way to utilise local energy sources, such as wood fuels, agrobiomass, biogas and peat, and heat loads for electricity generation. New technologies to utilise ever smaller heat loads and local renewable fuels with higher power-to-heat ratios are under development. Fixed and fluidised bed gasifiers connected to combustion engines using solid biofuels are presently under commercialisation. Stirling engines, gas turbines and fuel cells need high value fuels, such as gaseous and liquid biofuels or pellets. Use of natural gas networks for the delivery of biogas and other biomass-based gases is one possible option for enabling small-scale CHP plants using bioenergy.

Concept of combined heat and power production could be widened to the distributed production of cooling or desalination of seawater. Mills of the forest and food industry sectors provide an optimal platform for biorefineries that could generate, in addition to steam and electricity, also liquid biofuels for the transport sector and also green chemicals and other biogenic products. Integration of the industrial processes and energy production would increase total efficiencies and decrease specific investment costs.

5 References


Environmental Impacts of Future Energy Systems

Martin Pehnt
IFEU Institute for Energy and Environmental Research Heidelberg GmbH,
Wilckensstr. 3, D-69120 Heidelberg, martin.pehnt@ifeu.de, ++49 (6221) 4767-36

Abstract

New energy technologies are currently investigated in R&D and promoted in the political arena. Before these technologies enter the market, their environmental superiority over competing options must be asserted based on a life cycle approach. However, when applying the prevailing status-quo Life Cycle Assessment approach to future energy systems, some drawbacks arise. This paper investigates the environmental performance of several future energy systems (carbon capture and storage, micro cogeneration and photovoltaics) and describes associated methodological issues and instruments for dealing with the future dimension of these technologies.

1 Introduction

A number of new energy technologies are currently entering the energy market or are, at least, investigated with respect to their diffusion opportunities into the energy market. Technological advances in the field of distributed and renewable energy systems, the requirement of climate gas mitigation and electricity system capacity deficits, as well as market restructuring and deregulation have led to an increasing interest in these innovative technologies.

The environmental compatibility of such systems is an essential prerequisite for a positive assessment. Typically, the environmental performance of products in general and energy systems in particular are measured using Life Cycle Assessment. The two key elements of LCA are

- assessment of the total life-cycle (“cradle-to-grave approach”) of a given energy conversion technology, including the exploration, processing, transport of materials and fuels, the production and operation of the investigated energy conversion units, and their disposal/recycling; and

- assessment of different environmental impacts on resources, human health, and ecosystems.

An LCA basically consists of four steps: (1) a goal and scope definition, (2) an inventory analysis involving data collection and calculation procedures, (3) an assessment of potential impacts of the inputs and outputs of the inventory analysis, categorizing and aggregating the environmental interventions. For that purpose, impact categories, such as global warming, eutrophication, acidification, toxicity or summer smog are defined and characterisation factors are calculated, which describe the contribution of different substances to that particular impact category (e.g. CO₂, CH₄ or N₂O to global warming).
(4) Through interpretation, the findings of the inventory analysis and the impact assessment are combined in order to draw conclusions or formulate recommendations. However, the assessment of environmental impacts of future energy systems on a life cycle basis (Fig. 1) cannot follow the standard approach. Uncertainties, data gaps, modified energy system layouts and different physico-technical properties of the system make adaptations in the methodology necessary (Table 1):

- **Future character of the foreground system.** In LCA terminology, foreground systems are defined as consisting of processes, which are under control of the decision-maker for which an LCA is carried out. (Frischknecht 1998; Grunwald and Langenbach 1999) The future character of the foreground system can develop in different respects:
  
  Many of the systems under investigation have not yet been realised on a large scale, if at all. For instance, the performance of small Stirling engines for single-family applications has not yet been monitored with statistical significance (chapter 3). Likewise, in carbon capture and sequestration processes with chemical absorption, one – environmentally significant – step, the solvent regeneration, is still burdened with large uncertainty (chapter 2).
  
  Thus the following question arises: What is the improvement potential of these technologies compared to competitors, e. g. due to process and system innovations, progress of technical performance and production processes of systems, fuels and ancillary materials (e. g. wafer losses, biomass cultivation, etc.), diffusion effects (e. g. "ecology of scale": lower production impacts due to higher sales numbers), and increasing complexity of the systems, e. g. due to more integrated system design (use of co-products)? Ultimately, the uncertainty with respect to the development of these different dimensions leads to data gaps in the LCA model.

- **The often distributed nature of the energy systems requires further activities to monitor not only life cycle, but also regional and local environmental impacts.** For instance, in the case of reciprocating engine micro CHP (chapter 3), not only the overall pollutant emissions, but also local air quality issues need to be taken into account. Toward this end, analyses of local air quality are required. The distributed location of some of the future energy systems (e. g. photovoltaics) might also have impacts on consumer behavior, e. g. increased

---

**Fig. 1 Environmental interventions of future energy systems**

Risø-R-1517(EN) 297
Future energy systems will often exhibit low direct emissions from the use phase (e.g. pollutant emissions). Therefore, the environmental contribution of the other life cycle stages, namely the production of fuel and power plants, increases in relative importance. Also, the more sophisticated design of future power plants might involve more environmentally problematic materials. For example in fuel cells, catalyst materials (platinum group metals) and graphite (PEFC), nickel (MCFC) or rare earth materials are among the more environmentally costly materials (Pehnt 2003).

The transformation of the overall “background system” (which is not part of the actual object under investigation, but which provides, for instance, auxiliary materials, energy, etc.) significantly impacts the assessment of the energy systems under study. However, not taking these transformation processes into consideration could lead to self-fulfilling prophecies (for instance, assuming electricity mixes for Si wafer production for solar cells leads to significant impacts which are not inherent to solar cell production, but imported into the system from the fossil system; chapter 4). The changing background system might also concern the competing technologies. For instance, today a micro CHP system competes with a gas condensing boiler rather than with an average heating system. The question of the development of the background system also leads to a time dimension: How fast will the background system change?

The differing generation characteristics, e.g. of fluctuating renewable electricity generation systems, require modelling of feed-in, storage, and backup systems.

Another time aspect of assessing future energy systems is the time span which is covered by the analysis. Consider, for instance, a system with a certain leakage rate of a substance (such as CO₂ from a geological carbon storage formation). The question arises: Which is the appropriate integration interval of this assessment?

To deal with these issues, different approaches have to be chosen. Forecasting is necessary whenever environmentally relevant processes or components have to be assessed based on systems of an immature technology standard. Very often, the forecasting of the use phase, i.e. the performance, emission factors etc., can be derived either from process modelling, target data from manufacturers information, or emission levels required by environmental legislation.

It is more difficult, however, to determine the impacts from the production of future energy technologies which are, at the time of the LCA, very often produced on a lab-scale only. Different cost estimation methods have been developed in management sciences, such as subjective assessment methods, regression analysis, or system modelling (Pehnt 2003). Other approaches include interactive technology foresight processes integrated into LCA (Borup and Andersen 2003), expert panels which deliver input data for Monte-Carlo simulations (Contadini et al. 2002), and scenario technology (Weidema et al. 2002).

In the following chapters, the focus will not be on the methodological aspects, but rather on the application of the methods to three concrete examples of electricity-generating systems: carbon capture and storage, micro cogeneration, and photovoltaics.
Table 1: Aspects regarding the assessment of future energy systems

<table>
<thead>
<tr>
<th>Examples</th>
<th>Carbon Capture and Storage (CCS)</th>
<th>Micro CHP</th>
<th>Photovoltaics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physico-technical properties of the system</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decentralised systems</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low emissions in operation phase</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission source closer to recipient, impacts on local air quality</td>
<td></td>
<td>Decentralised installation: higher awareness for energy consumption</td>
<td></td>
</tr>
<tr>
<td>Fuel cells or Stirling engines: lower direct emissions, therefore increasing relevance of system production and fuel supply</td>
<td>No direct emissions, therefore high (relative) relevance of system production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluctuating energy supply → requirement of backup services</td>
<td>Regulating energy and load-levelling</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Future character of the product (foreground) system</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System innovation, progress of technical performance (life time, efficiencies, emissions, etc.)</td>
<td>Progress in carbon capture and power plant technologies (e. g. improved solvents, IGCC) lowers specific energy demand</td>
<td>Condensing operation, improved burner design (e. g. FLOX burners), better thermal integration</td>
<td>Increased life-time and efficiencies of PV modules</td>
</tr>
<tr>
<td>Progress of the production processes of systems, fuels and ancillary materials</td>
<td>Fuel cell micro CHP with lower catalyst loading</td>
<td>Reduced wafer losses, solar Silicon, EDFG, etc.</td>
<td></td>
</tr>
<tr>
<td>Diffusion effects, “ecology of scale”, up-scaling technologies</td>
<td>Lower production impacts due to higher sales numbers (fewer fixed impacts per unit)</td>
<td>Lower production impacts due to higher sales numbers (fewer fixed impacts per module)</td>
<td></td>
</tr>
<tr>
<td>Increasing complexity of the systems, e. g. due to more integrated system design</td>
<td>Combined production of heat and electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Future development of the background system</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Changing benchmark technologies (e. g., micro CHP today competes with condensing boilers rather than low efficiency boilers)</td>
<td>Electricity for wafer production, steel and aluminium for module support</td>
<td></td>
</tr>
</tbody>
</table>

2 Future Character of the Foreground System: The Example of Carbon Capture and Storage

Carbon dioxide capture and storage (CCS) is the capture of the CO₂ from the a flue gas stream from any point emission source, such as power plants, its compression, transportation, and subsequent storage in carefully selected storage sites, such as depleted oil and gas fields, aquifers, coal formations, and other geological reservoirs. CO₂ capture processes can be divided into three general categories: pre-combustion separation, oxy-fuel combustion, and post-combustion separation.

CCS has only rarely been implemented, mostly in the context of enhanced oil recovery. Therefore, coal power plants with CCS are a good example of future technologies that are characterized by a high degree of technological and infrastructural uncertainty. A detailed life cycle analysis (LCA) of the carbon sequestration paths was performed at IFEU (Idrissova 2004). The investigation involved analyzing the environmental characteristics of carbon dioxide capture and storage from fossil-fired power plants as a  

---

1 This chapter is based on a thesis supervised by IFEU (Idrissova 2004).
means of greenhouse gas mitigation in comparison with conventional and advanced power generation. Additional environmental aspects, such as local risks due to sudden releases of CO₂, groundwater issues, micro-seismic activities, etc. cannot be covered with LCA.

The LCA model was developed for a conventional lignite power plant (LPP), lignite power plant with CO₂ recovery by chemical absorption, an integrated gasification combined cycle (IGCC) power plant without CO₂ recovery and an IGCC with CO₂ separation by physical absorption. From the impact categories implemented in the model, here we report only the cumulated Energy Demand (CED), based on the lower heating value of fossil fuels and the fission heat of nuclear materials, and the Global Warming Potential in CO₂ equivalents.

The 600 MWₑl conventional lignite power plant was set as a reference power plant with a net efficiency of 41 %. Further power plants that were investigated included a 600 MWₑl IGCC power plant with an efficiency of 43.6 % without CCS and an IGCC plant with CCS. The CO₂ from the conventional lignite power plant is captured by an already mature and commercial technology of chemical absorption, a very energy-intensive process due to solvent regeneration. In the case of the IGCC, the more favorable physical absorption in terms of energy can be applied. For the recovery of CO₂ from the solvent in the regeneration tower, thermal energy in the form of steam is obtained from the steam cycle of the power plant. This results in a decrease of power production (energy loss), and the thermal energy can be converted into an “electric equivalent” taking into account the decrease in the performance of the steam turbine. For the scenario in this model the energy requirement for the 20 % solvent concentration is estimated as 0.38 kWhₑl per kg CO₂ (Göttlicher 1999), and is considered as a “base” case.

Due to the complexity of the chemical absorption, there is a certain degree of uncertainty in the estimation of the energy penalty. The variation of the solvent concentration in the chemical absorption changes the energy requirement and thus affects the total performance of the power plant. This is a typical uncertainty of high relevance and high time-dependency and thus requires further consideration. Here, we used chemical process calculations for the capture process with different solvent concentrations, as carried out by Göttlicher (1999), and implemented these data points in a sensitivity analysis.

The captured gas is then compressed to the required density level suitable for transportation and is directed via pipelines to the storage site. The length of the pipelines is another parameter for the sensitivity analysis (variation from 300 km to 900 km) due to the additional energy required for compression along the pipeline in order to compensate the pressure drop.

The storage site is assumed to have a zero leakage rate in this particular study. However, this is a question of further investigation and research in terms of integrity and availability of storage reservoirs, as well as of the acceptable duration of the storage and the subsequent monitoring of the site. The overall complexity of geological underground storage of CO₂ thus does not allow estimating a “general” leakage/seepage rate which could then be used in LCA or similar studies, as it is a parameter defined specifically for each storage location. Different studies are being carried out to address this issue. (Hepple and Benson 2003; Chalaturnyk and Gunter 2004). The important factor is the rate of surface seepage that could be acceptable in order to ensure the effectiveness of CCS. As long as the leakage rate is above zero, the result of the greenhouse gas
assessment obviously depends on the upper integration limit: If we assume a leakage rate of 0.001 % per year, then after 1000 years, 1 % of the CO₂ will have leaked into the atmosphere. Ultimately, with an extreme long-term perspective, the full amount of CO₂ stored underground will be released.

The LCA results using 0 % leakage and including the infrastructure (pipeline, carbon capture equipment, etc.) can be seen in Fig. 2 in which all four power generation options are considered and two selected impact categories are compared. As seen from that figure, the lignite power plant with CO₂ recovery has the highest cumulative energy demand (CED) in comparison with the reference power plant. The implementation of the advanced IGCC power plant with its higher efficiency would make it possible to reduce global warming (GWP) by 7 % compared to the conventional lignite power plant. Integrating CCS by chemical absorption in the conventional power plant would cause a 67 % increase in energy demand, whereas a CO₂ removal by physical absorption in the IGCC increases energy demand by only 20 %. This difference can be explained by higher energy demand of chemical absorption on the one hand and the higher IGCC efficiency on the other hand. The higher energy demand of CO₂ sequestration paths implies subsequently higher environmental impacts that are associated with coal mining, such as deterioration of area, ground water issues and so forth.

Whereas the energy penalty in the power plant due to CCS and the leakage rate are significant parameters, the effect of other life cycle stages (e. g. compression along the pipeline) and system components (e. g. construction of the pipeline) are only of minor importance. The results for other impact categories will be part of a separate publication.

![Fig. 2: Cumulative Energy Demand (CED) and Global Warming (GWP) of four power generation options (conventional lignite power plant LPP and integrated gasification combined cycle IGCC with and without CCS). LPP Variation 1: increase in solvent concentration to 40 %, variation 2: pipeline length increase to 900 km. IGCC Variation 1: plant efficiency increase to 50 %, variation 2: pipeline length increase to 900 km.](image-url)
3 Localized Environmental Impacts: The Case of Micro CHP

Micro CHP (combined heat and power production) or micro cogeneration is the simultaneous production of heat and power in a single building (Harrison and Redford 2001) based on small energy conversion units (e.g. reciprocating or Stirling engines, fuel cells). The heat produced is used for space and water heating and possibly for cooling; the electricity is used within the building or fed into the grid.

A detailed Life Cycle model of micro CHP, including the production of the power plant and the fuel supply, is devised and described in Pehnt et al. (2005). To take into account the co-product heat, an “avoided burden approach” was chosen. That is, we regard electricity as the main product, while generated heat is credited, and we analyze the replacement of a gas condensing boiler by a variety of micro CHP systems. The question answered through this substitution perspective is: Which environmental impacts do micro CHP systems have if we install them instead of a modern gas condensing boiler?

The micro CHP case study demonstrates two future aspects: data gaps due to uncertain system properties and more localized environmental impacts. Whereas the latter is dealt with further below, the first is particularly relevant for fuel cells as the least mature among the micro CHP technologies. Since they are still in the field-testing phase, the environmental performance of these technologies is still unclear. For instance, the estimates of total efficiencies range from 80 to 90 %. In the LCA presented in Fig. 3, this is covered by using default estimates and bandwidths to characterize the uncertainty of the data.

As far as the reduction of GHG emissions is concerned, the assessment shows that most micro CHP systems which are operated with natural gas are superior not only to average electricity and heat supply, but also to efficient and state-of-the art separate production of electricity in gas power plants and heat in condensing boilers (Fig. 3). This is true, despite the strong dependence of the results on the electrical and thermal efficiency of micro CHP technologies and further parameters such as methane emissions from reciprocating engines. In fact, lower GHG emission levels can be achieved at an electrical capacity of up to five orders of magnitude smaller than large gas combined-cycle power plants. Even larger reduction effects could be achieved if heating systems based on more carbon-intensive fuels, such as diesel oil, were to be replaced. The GHG advantages of micro CHP plants are comparable to district heating with CHP.

The performance of micro CHP technologies with respect to climate and resource protection depends mainly on the total conversion efficiency (including the thermal output of the system) that can be achieved. In some cases, an unfavorable heat integration of micro CHP systems may lead to operation at the lower end of the assumed bandwidths of total efficiency. In such cases, CHP systems come rather close to the GHG emissions of electricity production in modern combined cycle plants without CHP. Optimizing micro CHP implementation thus involves careful integration into the supply object.

Under the assumption that gas-condensing boilers are the competing heat-supply technology, all technologies (fuel cells, reciprocating and Stirling engines) are within a very narrow range, with the exception of the small Stirling engine, which features lower electrical and total efficiency. For reciprocating engines, the values for methane emissions due to unburned natural gas vary considerably. Therefore, the error bar for this
Environmental impacts other than those related to climate and resource protection relate more specifically to technology. Whereas emissions of air pollutants are extremely low for fuel cells and Stirling engines (as long as these use innovative flameless burner technologies), reciprocating engines emit more significant amounts of NO\textsubscript{x}, CO, and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics (lean operation or \(\lambda=1\), partial load or full load, etc.), and on the age and maintenance of the systems (catalyst exchange, engine characteristics, etc.). Thus, large bandwidths characterize this system. As a consequence, acidifying emissions of small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in the latter (Fig. 3).

When interpreting the LCA results for pollutant emissions, it is equally important to evaluate the impact of these emissions on the recipients' side: How does the local air quality change due to the emissions? This is even more important because we talk about a decentralized energy system with the emission source being close to the potential damage location. To address this question, the environmental relevance of the additional NO\textsubscript{x} emissions of reciprocating engines were assessed. For this purpose, a dispersion calculation for a virtual residential area was carried out, based on the software package AUSTAL2000 (2003). For this calculation, it was assumed that, in a residential area based on multi-family residences, one third of the houses would be equipped with a reciprocating engine. This corresponds to 100 systems in a 1 km\textsuperscript{2} area. In addition, avoided air pollutant releases due to the substitution of an alternative gas heating system are accounted for.

With respect to technical parameters, we conservatively assumed 5000 hours of full load operation per year, an NO\textsubscript{x} emission factor of 300 mg/Nm\textsuperscript{3} (expressed as NO\textsubscript{2}), and a share of 10\% NO\textsubscript{2} of primary NO\textsubscript{x} emissions. This latter assumption is of great importance, because NO\textsubscript{2} is of primary environmental concern. A site that has a flat topography and relatively critical weather conditions was selected: non-uniform wind distribution, large share of stable weather situations, and low wind speed, which tend to lower the dispersion of pollutants. The surface texture corresponds to that of an urban area.

Fig. 4 depicts the additional annual average concentration of NO\textsubscript{2} in the residential area due to net emissions from reciprocating engines. The annual average of 0.6 µg/m\textsuperscript{3} can be compared to the permissible level for the annual average NO\textsubscript{2} concentration; the German limit is 40 µg/m\textsuperscript{3}. The air concentration associated with the installation of the 100 units is very low – below a level of irrelevance, which is by German law defined as 1.2 µg/m\textsuperscript{3}.
Fig. 3. Life cycle GHG (above) and acidifying (NOx, SO2, NH3) emissions of micro CHP technologies compared to large CHP and conventional electricity production in the year 2010.

Functional unit 1 kWh electricity at low voltage level. CHP co-produced heat is credited with a gas condensing boiler ("avoided burden").

Fig. 4. Annual average concentration of NO2 in ambient air (µg/m³) in a residential area due to installation of 100 reciprocating engines per km² (permissible level: 40 µg/m³).
Consequently, with respect to the impact on ambient air quality, reciprocating engines are not critical under the given circumstances. Other emission sources, particularly from transportation, dominate the overall level of air quality. However, complex terrain (e.g., a narrow valley) might cause higher pollutant concentrations in certain places as calculated here.

4 Transformation of the Background System and Dynamic LCA: The Case of Photovoltaics

Not only the product system itself, but the background system which provides materials and services to the system under investigation can be in a process of transformation. The combination of changes in the foreground and background system could ultimately lead to a substantial change in the environmental performance.

As an example, Fig. 5 shows results of a dynamic LCA for a polycrystalline photovoltaic system and the influence of various optimisation parameters. The example is taken from a project which investigated the (environmental) implications of a widespread implementation of renewable energy carriers (DLR, IFEU, WI 2004).

The following parameters – which are both environmentally relevant and strongly time-dependant – are varied:

- **Future power plants.** Production of photovoltaics requires large amounts of electricity. Rather than using an average electricity supply mix as input, we assume that the power plant portfolio develops according to a “sustainability scenario”, meets a climate reduction goal of -80 % by the year 2050 and exhibits significant contributions from renewable energy carriers. We analyze a long-term development, taking the year 2030 as reference. An extrapolation of the efficiency and emission development from fossil power plants according to DLR, IFEU, WI. (2004) is realized alongside the adapted shares of energy carriers.

- **Aluminum and steel.** Future development concerns particularly the reduction of electricity demand, the respective power plant mix for the production electrolysis and the recycling rate (EAA 2000; Rombach et al. 2001).

- **Technology parameters.** Further time-dependant parameters cause an increase in module efficiency and life time, reduced wafer thickness and process losses at silicon wafer production.

Table 2: Parameters varied in the dynamic LCA of p-Si photovoltaics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel production</td>
<td>Scrap share 46 %, electricity 2010</td>
<td>Scrap share 75 %, electricity 2030</td>
</tr>
<tr>
<td>Aluminum production</td>
<td>Scrap share 85 %</td>
<td>Scrap share 90 %, reduced electricity demand for electrolysis</td>
</tr>
<tr>
<td>Electricity production</td>
<td>Business as usual electricity mix 2010</td>
<td>“Sustainable” Electricity mix 2030</td>
</tr>
<tr>
<td>Life time PV system</td>
<td>25 years</td>
<td>30 years</td>
</tr>
<tr>
<td>Module efficiency</td>
<td>13.4 %</td>
<td>17.8 %</td>
</tr>
<tr>
<td>Wafer thickness / Sawing loss</td>
<td>300 µm/200 µm</td>
<td>150 µm/150 µm</td>
</tr>
</tbody>
</table>
With regard to the greenhouse effect, each of the first three dynamic parameters constitutes a decrease of about 20%. Although the production of Silicon substantially contributes to the greenhouse effect, the smaller wafer thickness only makes a smaller difference. This is also due to the fact that the improvement step is applied to an already optimized system. Life-time and module efficiency are of the utmost importance for minimizing acidification.

![Fig. 5: Dynamic LCA of renewable energy systems, taking photovoltaic as an example. The representation is based on the environmental impacts of the non-dynamic system (=100 %).](image)

Overall, the development of optimization potential and the improvement of materials and energy supply produce a 50% reduction of the environmental impacts. Together with quantified optimization steps, it is possible to further reduce environmental impacts, particularly by recycling wafer and module components (Frisson et al. 1998).

It is interesting to note that advances with regard to “external” services that originate from conventional energy and transport systems, for instance, improved electricity or process heat supply for system production, ecologically optimized transport systems for the biomass transportation, could potentially lead to higher ecological impacts, because the attainable credits for by-products (“avoided burden”), e.g. glycerin in bio diesel production, are also lower.

Nevertheless, the combined effect of the three progress (advance) factors will bring about a substantial reduction of environmental impacts. A dynamic LCA perspective, thus, appears essential in the overall assessment of future energy technologies.

### 5 References


Acknowledgement

The work described in the paper was funded under the socio-ecological research framework recently launched by the German Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF).
Session 12 – Innovation and Technology Development

Chairman: Erik Lundtang Petersen, Risø National Laboratory, Denmark
Triple helix innovation as a model for developing sustainable waste incineration solutions

Karen Hvid Ipsen

R&D-coordinator, M. Sc. Chem. Eng
Elsam A/S
Overgade 45
7000 Fredericia
DENMARK
Phone (+45)76222000, direct phone (+45)79233220, email: khi@elsam.com

Abstract
Europe and near-Europe Asia produce around 3,000 million tons of waste annually. Their challenge is to reduce the amount of waste generated and to increase the recycled waste volumes. Incineration is one of the reduction options available. However, the employment rate of this option varies considerably across the continent, and today only about 20% of household or industrial waste is incinerated with energy recovery. Europe cannot afford ignoring an energy resource of this magnitude, and incineration will and must play a part in a sustainable energy future for Europe.

Waste is, however, a difficult fuel as it gives rise to an extremely corrosive internal environment and a great technical challenge as regards air pollution control (APC) and disposal of residues. With the efficient APC technologies available today, residues is the major emission pathway from incinerator to environment. Due to high concentrations of trace metals and organic pollutants, reutilization of APC residues has still not been possible.

Technical developments alone do not solve society’s problems. As incineration technology develops, it is a challenge to ensure the presence of a contemporary, robust policy framework and public acceptance of the technology.

An integrated development pathway, in which public authorities, industry and research institutions jointly contribute to the solution, is known in triple-helix innovation. A number of Danish partners have recently begun an APC residue development initiative inspired by this.

The paper presents the Danish APC residue initiative whose very ambitious goal is to develop sustainable technical solutions allowing for the subsequent utilization of APC residues. The initiative comprises industrial partners driving the technical development, universities securing the development and dissemination of essential environmental process knowledge, as well as the understanding by public authorities for the corresponding policy framework development.

Background

In Europe demand for energy is rising; the annual growth rate from 1995 to 2001 was 7%. This increasingly concerns European politicians and leaders on two aspects:
- the impact on the environment, especially the climate; and
- the geopolitical implications of the continuing dependence on overseas suppliers of energy products, especially oil.
Europe needs to develop a stable and sustainable energy supply for the future.

At the same time, the number of European households is expected to grow whilst decreasing in size and the average age is rising. These demographic changes combined with a rise in GDP add pressure on the energy supply (increasing domestic demand for electricity and transport) and at the same time will probably also force an increase in amount of waste generated (single/divorced households generally being less efficient). This trend is already seen e.g. in the rise in packaging waste across Europe. (EEA, ref. /1/).

This presents Europe with a double challenge:
- to cover the rising demand for energy (preferably at the same time increasing self-supply and renewables coverage), and
- to efficiently handle and dispose of more and more waste.

**Waste and energy**

Incineration of waste – with energy recovery – may contribute to the solution of both challenges. Today, 6% of the primary energy consumption in Europe (EU15, 2001) is covered by renewable energy sources. Electricity consumption (EU25, 2001) is 14% renewables, primarily hydropower, electricity from waste incineration currently amounts to less than 4% of the renewable electricity generation in Europe (Eurostat and EEA). (Ref. /2 and 5/). The penetration of renewables (solar, wind, waste and biomass) in selected European countries is seen in figure 1.
Table 1. Main waste streams in Europe

<table>
<thead>
<tr>
<th>Type</th>
<th>Short definition</th>
<th>Amount</th>
<th>Disposal</th>
<th>Energy content</th>
<th>Energy potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal Waste</td>
<td>Waste generated by households and commercial activities similar to households</td>
<td>14% of waste generated in Europe, totaling in excess of 306 million tons annually</td>
<td>Predominantly landfill. Approx. 57% in Western Europe, nearly 100% in Central &amp; Eastern Europe</td>
<td>LHV varies, generally around 9-11 MJ/kg</td>
<td>Approx 2,400 PJ of primary energy annually (~57 Mtoe) Potentially 160 TWh of electricity</td>
</tr>
<tr>
<td>Industrial waste</td>
<td>Reject from industrial processes</td>
<td>25% of waste generated in Europe, totaling approx. 740 million tons annually</td>
<td>Not known. Presumably a significant amount is landfilled along with municipal waste</td>
<td>1/3 of the waste presumably nil (metals and ceramics); 2/3 with LHV estimated at 10-20 MJ/kg (food, paper, chemicals, wood)</td>
<td>Approx. 3-4,000 PJ of primary energy annually.</td>
</tr>
<tr>
<td>Construction and demolition waste</td>
<td>From buildings and civil infrastructure</td>
<td>25% of waste generated in Europe</td>
<td>Landfilled or recycled (up to 80% recycled)</td>
<td>Low, some energy from woody wastes are available</td>
<td>Low</td>
</tr>
<tr>
<td>Mining waste</td>
<td>Soil, overburden, slag etc.</td>
<td>20% of waste generated in Europe.</td>
<td>50/50 landfill or reused for land restoration.</td>
<td>Practically nil</td>
<td>None</td>
</tr>
</tbody>
</table>

Not quantified: Hazardous waste, ELV and WEEE waste, energy production wastes, agricultural waste

Data source: European Topic Center on Resource and Waste Management, Ref. /1/

The cornerstones of Europe’s strategy for coping with waste are:
1) waste prevention  
2) waste recycling  
3) energy recovery and  
4) disposal such as landfilling and incineration without energy recovery.

For many years Waste-to-Energy has been an integral part of the energy supply in Denmark (ref. /4/) (providing currently 4.2% of the domestic electricity supply and 17.6% of co-generated district heating). The Danish history of accepting waste incineration is however not prevalent in Europe (see fig. 1) and there is still a large potential for energy recovery from waste.
Europe.

and disposal as a prerequisite in order for this technology to be regarded as a sustainable energy solution for
dictates very strict emission standards regarding incinerator emissions, and the 1999 landfill Directive, which
largely responsible for the public resistance. The 2000 European Union Directive on Waste Incineration, which
concern regarding incinerators as environmental hazards – the emissions of dioxins and heavy metals being

The reluctance in some countries to use waste incineration as an energy provider is primarily caused by the
care. The 1999 landfill Directive, which restricts the landfilling of biodegradable waste, may together overcome this resistance.

Triple helix Innovation

The concept of triple helix innovation, described by Etzkowitz (ref. /7/) and others, proposes a more efficient
innovation process by having an intertwining reciprocal relationship between academic research, industrial
sponsorship and governmental and institutional support. The triple Helix model predicts that the increased
integration speeds society’s realization of benefits from innovation by facilitating technology transfer and capi-
tal investments.

In continuation of this, Dambrowitz (ref. /8/) and others proposes that engaging a “fourth helix”, the general -
and indeed international - public is of equal importance. The fourth helix, in whose interests government insti-
tutions are called upon to act, is needed to provide feed-back on preferences and goals for society at large.

The Tripel Helix Innovation model of late 2003 inspired the formation of a Research and Development col-
laboration:

The Danish MSWI-APC residue initiative

With the efficient air pollution control (APC) technologies available at present, and indeed compulsory for
MSWI in Europe, today the wastes produced from flue gas cleaning is one of the major emission pathways
from incinerator to the environment. Therefore, energy recovery from waste incineration has residue control
and disposal as a prerequisite in order for this technology to be regarded as a sustainable energy solution for
Europe.

Figure 1: Incineration capacity in selected European countries

![Incineration capacity in selected European countries](image)

The Danish MSWI-APC residue initiative
In a Danish context, with the current waste strategy (ref. /9/) aim for 2008 of “a Danish solution for the management of [MSWI] flue gas cleaning products”, the Danish government recognizes this fact. In recognition of this, in 2003 a group of major Danish MSWI operators initiated the formation of “The Danish MWSI-APC residue R&D collaboration” (the APC initiative).

The official inception date was January 1st, 2004, the industrial originators being:
- Amagerforbrænding I/S (incinerates approx. 440,000 tons/year) (ref. /10/)
- Vestforbrænding I/S (incinerates approx. 500,000 tons/year) both operate in the greater Copenhagen area on Seeland, (ref. /11/) and
- Elsam A/S, the largest Danish power producer (also operating waste incinerators in 6 cities in Jutland, incinerating approx. 700,000 tons/year) (ref. /12/).

Elsam, Vestforbrænding and Amagerforbrænding jointly carry the financial costs of operating the APC initiative. The initiative is scheduled to run for five years, with an annual budget (excluding management costs and public/EU funding as available) of 400k€.

But knowing that at thorough scientific basis was - and is - necessary for the initiative to succeed, from day one the industrial operators sought, and succeeded, in affiliating the Danish Technical University (DTU, Institute of Environment and Resources) with the work and goals of the initiative. The role of DTU is to ensure that solid scientific methodology and conclusions underpin projects and results.

APC Initiative goals

The formulated goals of the APC-initiative are

- To identify, manage or participate in developing new or improving existing technologies or methods for the treatment of MSWI APC-residues, with particular reference to entirely or partly re-using the APC-products or components extracted there from for beneficial purposes.
- To compile and prepare documentation for the environmental and economical effects of such technologies and methods, and to ensure that an unbiased and satisfactory decision-basis is provided for the relevant Danish authorities on both political and local government levels.

The APC-initiative recognizes that the Danish government cannot provide exclusive support to (semi)private initiatives such as this with the risk of favoring this/excluding others; however it is the intention of the APC initiative to take action in close dialogue with the relevant authorities (primarily the Danish Environmental Protection Agency, DEPA) to:

- Seek a common understanding and evaluation of environmental and economic costs and benefits from further treatment and possible reutilization of MSWI APC residues, and in continuation hereof
- Ensure that the necessary policy frameworks supporting the sustainable treatment or disposal options are clear and present (primarily legislation, taxes and public planning)

APC Initiative actions

In order to meet the goals of the APC initiative, projects are initiated under the following five headings:

- Prevention and preprocessing
- APC residues for building and construction
- APC residues as an industrial resource
- Methodology and toolbox
- Policy framework and dialogue

The actions reflect the triple helix approach permeating the initiative. Technology development and innovation (the first three action areas) will be required in order to achieve the main goal of providing a sustainable (in both economic and environmental terms) Danish solution to the APC disposal needs. The industrial segment primarily drives these actions.

Methodology and toolbox projects are needed to compare the technical solutions in both environmental and economical terms, in order that the “right” long term solutions will eventually be selected. Methodology and toolbox projects are to a large extent developing and applying comparative Life Cycle Assessments (LCA) and Cost Benefit Assessments (CBA) to the various technologies. DTU and other industry independent research institutions drive the technology assessments.

Finally - hopefully - having found a long term sustainable solution, a dialogue will be initiated with policy makers, since adjustments to both environmental legislation and other policy instruments, such as taxes, are likely to be needed in order to establish and use the required industrial APC residue processing facilities. This brings the third strand in the triple helix into play.

The current project portfolio within the various action areas is seen from table 2:

<table>
<thead>
<tr>
<th>Action area</th>
<th>Project title</th>
<th>Project leadership and partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methodology and toolbox</td>
<td>APC Technology State-of-the-art Whitebook Environmental fate - Quantitative Prediction LCA tools for APC Solutions Comparison</td>
<td>Danish Technical University DTU, (as a PhD scholarship) DTU, (as a PhD scholarship)</td>
</tr>
<tr>
<td>Prevention and preprocessing</td>
<td>Waste characteristics and APC formation</td>
<td>Elsam and DTU, funding expected from TSO</td>
</tr>
<tr>
<td>APC for building and construction</td>
<td>APC in manufactured Light Aggregate APC in Concrete</td>
<td>Elsam Engineering., University of East London DTU, École Polytechnique Féd. de Lausanne</td>
</tr>
<tr>
<td>APC as an industrial resource</td>
<td>Salt and Lime Extraction from APC APC Classification for Industrial Use</td>
<td>AF, VF, DHI Elsam Engineering., (partners not yet finalised)</td>
</tr>
<tr>
<td>Dialogue and policy framework</td>
<td>APC legislation Review in Denmark and EU</td>
<td>Elsam Engineering</td>
</tr>
</tbody>
</table>

Table 2: APC initiative project portfolio

**Conclusion: Sustainable energy development for the future**

The Danish APC initiative has (not surprisingly) its roots in Denmark, but for the initiative to really succeed, we need to expand to a broader European level, and in this respect invite potential European partners to a dialogue and cooperation. The reasons are:

- The drive for a common European future and a common market requires solutions that are both competitive and widely accepted across the union.
European Union environmental legislation has a significant influence on national environmental legislation too. A solitary national approach in Denmark is not likely to succeed in the long term. Solutions pioneered in national states may on the other hand influence EU legislation (even though this may be a lengthy process).

Europe need untapped energy potential from waste incineration. Public acceptance of incineration varies greatly across the continent, ranging from broad acceptance in some States to savage opposition in others.

European legislation leaves very little room (at least in the short term) for not using incineration for waste disposal, and the question is (given current trends and experiences) whether in the long term Europe is able to solve the waste problem without incineration.

The challenge for Europe is to switch to greater energy self-supply using all renewable energy sources available, including waste incineration, and at the same time do this in an environmentally sustainable manner. This process requires massive public investments. Hopefully the Danish APC initiative will (in time) be seen as an example of how - inspired by the triple helix concept - academia, industry and government working together for a common goal could ensure broad public acceptance of both technology and investment as a sustainable solution for Europe.
References

3. Eurostat www.europe.eu.int/comm/eurostat
10. Amagerforbrænding I/S. Homepage www.amfor.dk (in Danish)
11. Elsam A/S. Homepage www.elsam.com
12. Vestforbrænding I/S. Homepage www.vestfor.dk (in Danish)
Innovation and Sustainable Development in the Energy Sector

Jürgen-Friedrich Hake, Dr. Regina Eich
Programme Group  Systems Analysis and Technology Evaluation (STE)
Forschungszentrum Jülich GmbH
52425 Jülich / Germany

1. Innovation - What does that really mean?

The concept of innovation initially subsumes a new product, a new material, a new service or a new process. In this context, it is emphasized that innovation involves intentional strategic actions.

Innovation denotes the implementation of new solutions on the market, associated with new factor combinations. Sustainable innovation designates factor combinations and new solutions that lead to a reduction of environmental pollution and resource consumption without resulting in any restrictions on other societal goals. This does not only include new technological solutions but also new services and new forms of organization.

Within the framework of research and development (often abbreviated to R and D or R&D), innovation designates a systematic search for new know-how and possible applications with the aid of scientific methods [Schröder 1999]. However, the results need not necessarily be a new product or a new method. It may rather be the extension or intensification of an existing knowledge base. The following features of innovation activities can be identified in the field of R&D:

- Uncertainty with respect to gaining new know-how,
- Uncertainty with respect to the utilization of the new knowledge,
- High demands on staff creativity, and
- Ongoing changes to the information on which project planning is based.

With respect to forms, a tripartite division can be made for the R&D sector:

1. Basic research,
2. Applied research, and
3. Development.

Generally speaking, since earliest times innovation has served to make mankind more independent of the whims of nature and at the same time to increase prosperity. However, since the end of the nineteenth century at the latest, "innovation activity" has increasingly also comprised the task of opening up new areas of business, creating jobs or bringing about necessary infrastructure changes. In this way, joint responsibility is thus transferred to innovation for preserving our environment from destruction – for example by reducing harmful emissions and saving valuable energy or, in the past, by establishing urban sewerage systems.
2. Challenges

The energy supply is the basis for prosperity and sustainable development for industry and society. According to the final report of the Study Commission "Protecting Mankind and the Environment" of the 13th German Bundestag, sustainability means "being able to satisfy the needs of a growing number of people today and in future, and at the same time maintaining a permanently inhabitable world for everybody under decent, safe conditions. This involves a wide range of economic, ecological, demographic, social and cultural problem dimensions which require global, regional, local and at the same time forward-looking action." In practice, implementation of the sustainability principle means that equal attention must be paid to economic, ecological and social aspects. The objectives of an energy policy, which are all of equal importance, are cost effectiveness, security of supply and environmental compatibility in the provision and utilization of energy. Political measures must be continuously reviewed with respect to their impact on the international competitiveness of the German economy, on jobs, siting decisions and their environmental compatibility. In this context, environmental compatibility means the prudent use of natural resources, minimal environmental pollution during energy production and consumption, and also efficient and economic handling of energy.

The energy economy and energy policy operate in an altered environment which is characterized by competition developing dynamically, both nationally and EU-wide as well as internationally, in the energy markets. This framework is characterized by EU law, by obligations from the Energy Charter Treaty, and also from obligations as part of WTO (GATT/GATS). The globalization trend and the changing EU and international competitive markets characterize the chances of the market participants and the opportunities for shaping national policy and underline the need for a competitive energy supply.

3. The Energy Sector in Relation to Society as a Whole

The boundary conditions for the German energy sector have been radically changed. Globalization and deregulation, climate protection and the debate about the use of nuclear energy, these are the challenges that society has to face. This involves setting the course for the future energy supply in the sense of sustainable development.

An energy supply with prospects for the future is of major economic, social and thus political significance. It should therefore be supported by a broad social consensus. In the past, it has proved impossible to achieve this consensus for a number of different reasons. It appears appropriate to focus and discuss the necessary reform processes within the framework of the following three issues:

1. Competition and regulation,
2. Efficient energy use, renewable energy sources and CO₂ reduction in an international framework,
3. Competitiveness of the German energy economy – security of supply and jobs.

The energy sector is of major significance for all sectors of the economy. This is true of all sectors of industry from energy utilization to energy provision. Only this holistic perspective makes it possible to see the outstanding significance of the energy sector as a production and consumption sector with considerable added value, job, investment and innovation potential. Energy is also an important siting factor. The provision of an economic, reliable and environmentally compatible energy supply is in the interest of industrial companies. Free-market processes ensure efficient supply and service structures. However, if market performance does not correspond to the objectives of energy, industrial and environmental policy then a political regulation function is required. This includes
cooperative solutions on the part of government, industry and consumers. In particular, due to the infrastructure character of the energy supply, the following tasks must be subsumed under the field of government action:

- Ensuring the effectiveness of competition and guaranteeing equal opportunities for German companies in the EU and international context,
- Ensuring security of the energy supply for all consumers,
- Precautionary measures for an energy crisis,
- Defining demands to be made on technical safety, and also the
- Implementation of an energy policy oriented to sustainability and precautionary principles (including integration of costs for environmental protection and resource consumption and their impact, which are not (yet) part of cost calculations on the part of companies, or have not yet been reached by the market (market failure).

Political measures must be continually reviewed with respect to necessity, duration, extent and control efficiency.

The aim of enhancing the competitiveness of the German energy supply, also oriented towards a positive effect on employment, involves increased investment activities in innovative technologies, processes and services. This applies both to the classical fields of the energy sector and also to the economical and efficient use of renewable energy sources.

### 3.1 Innovation activities in the energy sector

The energy sector is an extremely complex structure, which ranges from the extraction of energy carriers, their conversion into the secondary energy available on the market, through the distribution of this energy to the various sectors of our economy, up to the utilization – usually associated with a further energy conversion – for the provision of goods and services. Figure 1 gives an impression of this interlinkage and integration of the energy sector in our economic and private activities.

![Figure 1: (Energetic) interlinkage of the German energy sector](image)

The approaches to and implementation of innovations in the energy sector are equally varied. It can therefore be said that – as in other sectors – ground-breaking, completely novel approaches, such as the electrodynamic principle, the use of uranium as a new energy
carrier, or the internal combustion engine, occur very seldom, but that process improvements, also by using innovations from other sectors such as IT technologies, are continually taking place. The engine for these developments is not least the visions and also the tasks involved in connection with use – in the sense of the self-image moulded by society that arises with the demands for the services offered. This self-image can be described today by the concept of sustainable development. Especially in the energy supply sector (energy conversion sector), action according to this principle is by no means unknown since this maxim for action is followed according to the three-pillar approach in Figure 2– even if to varying extents – as a glance at the past.

![Figure 2: Dimensions of Sustainable Development](image)

If an attempt is made to assign the developments to the derived strategic criteria according to the three-pillar approach, then a shift in the weighting of the criteria becomes apparent which, in turn, can in part be explained by the objective necessity (need) or from the respective state of the art (and which perhaps indirectly represents an evolution up to and including the present sustainability approach).

In the immediate postwar years, attention was therefore focused on security of supply, which required the expansion or reconstruction of the infrastructure (integrated power grid, road and rail network) as a priority. In parallel, the reconstruction, and with increasing demand due to the start of economic growth, the construction of new energy conversion facilities and industrial plant. In each case, use was made of the state of the art, which led to both economic productivity and also, due to the large number of facilities required, to a leading role in the international context. Since this strategy also corresponded to the goals of the industrial companies, it was retained in subsequent years (competitive advantages from the companies' perspective and full employment meaning prosperity for society). Since energy efficiency also increased as a result of this strategy a positive contribution was also made to specific (i.e. per unit of output) environmental relief.
When the need to catch up and society's basic needs had been satisfied, the growing energy demand – in spite of the reduction of the specific environmental pollution – was increasingly perceived as a deterioration of the environment and thus criticized and remedial measures called for. Reactions to these conditions corresponded to the respective state of the art (dust: introduction of electrostatic precipitator throughout the country, policy of high stacks).

The gain in knowledge that, upon close consideration of the ecosystems, the policy of high stacks (dilution to an acceptable level) was incorrect led to the demand for "purification at the source". For the first time a major conflict of interests arose between operators and politicians since due to the deterioration of economic productivity – and efficiency – the operators feared competitive disadvantages due to environmental measures so that a negotiation process was required which led to a consensus in the adoption of the Directive on Large Combustion Installations. At the same time, this led to a considerably higher estimation of the "environmental pillar" for the future.

The development described here for industry and energy utilities also took place, and is taking place, in other sectors of the energy economy, for example with passenger cars: reduction of specific consumption (see figure 4), standards for exhaust gas purification (catalytic converters), unleaded and largely desulfurized fuels, or, for instance, in the case of domestic appliances (lower electricity consumption, energy-saving lamps) and also in the waste water sector (construction of sewage works throughout the country, improvement of retention measures).
Figure 4: Development of fuel consumption for newly registered passenger cars

At the same time as the conflict of interests described above, distrust of large enterprises and the associated so-called large-scale technology began to take root in society and obstructed or prevented the introduction (and the operation) of these technologies (examples: nuclear engineering, Transrapid train system, large traffic infrastructure projects, or the schadenfreude about the mishaps during the introduction of the Tollkollekt motorway toll scheme). This does not, however, represent a mistrust of technology in general, as shown by the widespread acceptance of, for instance, mobile phones or PCs – technologies whose direct personal benefit is recognized.

Figure 5: Development of nitrogen oxide emissions in Germany

Figure 6: Development of sulphur dioxide emissions in Germany
As the figures 5 and 6 show, in the case of air pollution control (and also water pollution control) a solution to the problems has been found, which, however, cannot be said to the same extent of CO₂ emissions. These emissions are also being reduced, amongst other aspects due to continually improved energy efficiency and economic structural change, but only to a slight extent, as can be seen from figure 7.

![Figure 7: CO₂ emissions in Germany](image)

No commercial-scale solution seems in sight for the next 30 years, and would in any case encounter the above-mentioned societal objections. Nevertheless – as in the past – there are a large number of small steps, initiated by innovations in various fields, such as materials science, sensor technology and control, which may lead to increased emissions reduction, but which are not all "economic sure-fire successes" but may, for example, be initiated by corresponding political boundary conditions. To this can be added other (induced) measures such as the insulation of buildings.

Successfully implementing innovations also means that sufficient innovations must always be kept in reserve. Successful introduction of an innovation also requires a suitable window of opportunity, both in willingness (acceptance) on the part of the user to make use of the innovation and also the technological environment (infrastructure, existence of suitable materials). Thus, for example, the first patent in 1807 for operation of a hydrogen engine was too early with respect to the technological environment and even today it is basically impossible to predict when a certain innovation from the reservoir of possibilities can be used. The probability is undoubtedly the greater the more closely the technology can be measured against existing technologies and whether it is a further development in trends that have already been successfully implemented in the past. Figure 8 shows possible further developments in power plant engineering for centralized electricity generation which would all lead to a reduction in CO₂ emissions if implemented.

The window of opportunity for a successful introduction of innovative technologies has already been mentioned. This is not unamenable to influence. CO₂ certificates are an example of possible political activities that make new low-emission, but not yet marketable technologies competitive by including external costs in economic decision-making processes. Other concepts currently under development still require time-consuming technological development. This is where the Lisbon process with its education and growth offensive can create an innovation-friendly climate which will ultimately also contribute to reducing the necessary development times and thus also to bringing forward the window of opportunity.
If more selective intervention is to made in the process then a picture must be obtained of the achievable benefits. This is very difficult in the complex energy sector, where everything is interlinked: halving the electricity consumption of a refrigerator may save, for example, 500 kg of CO\textsubscript{2}. However, it may only be 350 kg if 30\% CO\textsubscript{2} has already been saved during electricity generation. And of course it must always be assumed that the respective savings vary.


Since the future is unforeseeable, from the present point of view an innovation approach seems to be the better strategy. Preparing or creating innovations means being better equipped for the incalculabilities of the future. This statement is certainly also true of the European energy system since by their very nature energy systems have always been internationally oriented due to their energy purchases and interdependencies and therefore have a similar structure. To this extent, an orientation of the German energy system to the even more important European energy policy is not a fundamentally new demand.

European energy policy is oriented to long-term energy goals as already laid down in the 1995 white paper "An Energy Policy for the European Union". According to the white paper, energy policy must fit in with the general goals of the Community's economic policy. Furthermore, energy policy must, however, also pursue the special goals of harmonizing competitiveness, security of supply and environmental protection in the energy sector.

The principal goal of the EU energy policy set forth in the green paper is ensuring security of the energy supply for all consumers at an affordable price while at the same time maintaining environmental protection and encouraging healthy competition on the European energy market. Energies from renewable energy sources take on decisive significance for the diversification and sustainability of energy sources and for climate protection.

In connection with the Kyoto Protocol, the increase in energy efficiency has become more than ever an integral part of the Community's strategy. In April 2000, the Commission adopted a plan of action for improving energy efficiency in the European Community.

Moreover, in the white paper "Energy for the Future: Renewable Sources of Energy", the European Commission decided on a common strategy and a plan of action for the field of renewable energy sources to increase the proportion of renewable energy sources in the overall energy consumption in the next ten years. The primary goal of the European Commission is to raise the proportion of renewable energy sources in the overall energy consumption to at least 12 per cent by the year 2010. A "Campaign for the Breakthrough" is an integral part of the plan of action and the strategy for 2010 and is intended to act as a catalyst for the development of key sectors in the field of renewable energy sources, for which quantitative goals were set for 2003.

The "Intelligent Energy – Europe (2003 – 2006)" programme covering a number of years is intended to offer practical support for the energy policy laid down in the green and white papers. As a component part of this programme, the European Union has launched various research priorities – such as ALTENER, SAVE, STEER, SYNERGY and COOPENER.

The funding priorities in the SAVE Programme are to be found in the following areas:

- Tools for the take-off of the buildings directive,
- Schemes for the implementation of energy services in buildings, in particular retrofitting,
Public buildings as shining examples,
Promotion of best practice examples of high energy performance buildings, as well as
Instruments for energy management, including energy audits, energy accounting, benchmarking activities, voluntary agreements,
Energy services in SMEs, and
Polygeneration.

In contrast the funding priorities in the ALTENER and STEER programmes concern intensified research and promotion in the field of renewable energy sources for heat generation and the improvement of know-how for local agencies in the transport sector. The following concrete principle research topics can be mentioned:

- Compiling legislation, fuel standards and norms for RES heating systems,
- Supply chain and market structures for RES heat products,
- Public relations and training, as well as
- Training and education of local agencies in alternative fuels and energy use in the transport sector, and
- Support for local actors for collaboration in programmes and for project participation.

The European Union's SYNERGY Programme supports cooperation with non-member countries in the energy sector. Within the framework of this programme, cooperative projects are therefore to be realized which serve for the development, formulation and implementation of energy-policy strategies in areas which are of interest for the energy economy of both the EU and also non-member states. In accordance with the new guidelines, the programme focuses on improving security of supply in the Community and applicant countries and also makes a contribution to implementing the Kyoto Protocol. In addition to these programmes with a primarily specific and short-term orientation, the European Union is also attempting, as part of the Lisbon process, to more closely interlink the fields of energy, research and innovation.

A first – and also far-reaching – step in this connection was the adoption of the Lisbon Agenda. In March 2000 at the summit conference in Lisbon, the heads of state and heads of government of the European Union pledged themselves to the strategic goal of making the European Union the "most competitive and dynamic knowledge-based economy in the world" by 2010.

The so-called Lisbon Strategy was drawn up in advance of the meeting in Lisbon. Its main concern was to lay down a strategy for the economic and social renewal of the EU. In concrete terms, a number of quantitative and qualitative goals were laid down which are compiled in the following table:

- Average annual economic growth rate of 3% p.a.
- Raising the employment level to 70% (60% for women) by 2010
- Employment level of 67% for all persons gainfully employed and 57% for women by 2005
- Raising the employment level for older employees to 50% by 2010
- Continual increase in overall expenditure for the R&D sector to 3% of the GDP in 2010 – 2/3 of this expenditure is to be provided by the private sector
- Day-care places for 90% of children of kindergarten age as well as 33% of children under 3 years old by 2010
- Cutting by half the number of 18- to 24-year-olds who only have middle-school qualifications (O-levels) by 2010
- Implementation of the single-market directives by 2003
- Increasing the proportion of renewable energy sources in primary energy demand to 12%, in gross electricity consumption to 22% and in the transport sector to 5.75% by 2010
- Internet access for all schools by 2001
- Increasing government aid to developing countries to 0.7% of GDP by 2006

In principle, the individual goals of the Lisbon Strategy can be subsumed under the following key topics:

- Support for reasonable growth,
- Reduction of budgetary deficits,
- Realization of lower inflation rates and interest margins,
- Minimization of unemployment, and
- Achieving progress in productivity, amongst other measures by an increased focus on the field of innovation support.

The following aims were qualitative goals of the Lisbon Strategy of the European Union:

- Creation of a European research and innovation area (increasing the mobility of scientists / interlinking the centres)
- Creation of a favourable environment for SMEs (deregulation, SME charter)
- Speeding up the development of the single market (service directive / deregulation of the mains-locked services / creation of an European airspace / modernization of competition policy / Community patent)
- Creation of an information society (Internet access for schools)
- Modernization of the social systems and consolidation of social cohesion in the EU (modernization of the EU Social Agenda / equal opportunities for the disabled / equal opportunities for men and women / elimination of poverty / ensuring the long-term sustainability of the retirement pension schemes)
- Full employment through active job creation policy (improvement of the employability / structural reform of employment policy / good and flexible organization of working hours / incorporation of the social partners in the Lisbon goals)
- Sustainable environmental policy (compliance with the Kyoto goals / protection of biodiversity / policy of sustainability in four areas – climate change, transport, public health, natural resources)
- Budget consolidation and sustainability of public finances

The aim of the European Council was to employ a broad-based programme like the Lisbon Strategy to set in motion an overall reform process, with the aid of which individual mutually supportive reforms can be initiated in the Union's employment, finance, product and service markets.

The aim of the Lisbon strategy was very ambitious. The Lisbon Agenda is intended to make the EU the most competitive area in the world. Amongst other aspects, the Commission intends to promote the innovative power of the commercial enterprises by doubling the EU research budget as part of the 7th RTD Framework Programme (2006-2010).
5. Technology and Know-how – Innovations in the European Union

The first interim report on the Lisbon Strategy in 2004 showed that the scope for knowledge-based and technologically sophisticated growth in the EU has by no means been fully exploited.

Figure 8: Real GDP Growth in the EU-15, the acceding countries, US and Japan (1998-2003) in % change on previous year [Source: Eurostat/DG Research]

Although the European Union overtook the USA in productivity growth in the low-tech sector in the nineties, annual productivity progress in the information and communications sector at 1.5 percentage points remained below that of the American growth rates. Furthermore, the proportion of the EU-15 states' GDP in the high-tech sector of about 33% of the total GDP is five percent lower than in the USA (see figure 8).

The question behind these figures is: What are the reasons for the halting implementation of new technologies in the European Union? The answer is not so easy to find since there is no uniform trend in the individual member states.

In Sweden and Finland, figures for R&D expenditure are comparable with those of the international leaders. In contrast, the corresponding figures in the larger EU economies – such as France – only correspond to the international average. Furthermore, an unfavourable indicator is that the fraction of expenditure for information and communications technologies display a decreasing trend in the 15 EU member states.

It can be seen from these developments that research and development are not an outstanding feature of the European Union. The European Union as a whole invests a lower proportion of its GDP in R&D than, for instance, Japan or the USA. An extremely problematic aspect in this connection is that the expenditure for research and development in the Union's largest member countries does not display any increase. R&D expenditure in the French national budget, for example, has been decreasing continually for several years; in the UK
expenditure is stagnating and also Germany's expenditure in this field is lower than the GDP percentages of Japan or the USA (see figure 9).

Figure 9: R&D investment (€ billion, in current terms) in 1995, 1998 and 2001 [Source: OECD, Eurostat, DG Research]

This trend is not only identifiable in the government sector. These trends are also found in the field of company research. This should be almost be regarded as more critical than the "declining" figures on the government side since it is in particular research on the part of the private sector that is a decisive factor for the innovation dynamics of a country's economy. This can be explained by the fact that government R&D expenditure is more strongly focused on basic research. These funds thus have less impact on growth and modernization than application-oriented research in companies. However, the member states of the European Union (such as France, the UK or Italy) figure as "also-rans" in international rankings in this respect as well.

This has an impact on technology intensity – as a glance at the export statistics will demonstrate. The proportion of exports of high-tech products from the European Union is very low relative to the overall export figures. This naturally affects the EU's terms of trade. These figures fall off due to the negative high-tech export balance since the export of low- and medium-tech goods leads to lower relative prices and consequently to lower export revenues.

Of the leading industrial nations, the world export champion, Germany, only has a proportion of 15% high-tech exported goods in its total exports and is thus outstripped by countries such as Ireland, Finland or the new EU member Hungary.

Furthermore, expenditure for university education is below average in the European Union according to international standards. The EU average is crucially determined by expenditure in Germany, France and Italy, in which connection – as for R&D expenditure – a clear North-South divide (with higher expenditure in the Nordic countries) can be identified within the Union.

It is no exaggeration to speak in this context of a EU-specific combination of a high technological standard and in comparison a relatively large proportion of the population with a low or moderate educational standard. From a long-term perspective this will have counterproductive consequences. In this context, the low proportion of private expenditure for university education in comparison, for example, to the USA, can be characterized as typical of the European Union. In the USA, for instance, this is 1.6% of the GDP (1999),
which is not only significantly higher than government expenditure, but it also exceeds the total expenditure (public and private sector) in most EU countries.

Whereas in the USA efforts towards achieving a higher level of education are regarded as an investment in the national human resources, this expenditure is often merely regarded as a burden in European countries.

6. What is the Way Forward in the European Union?

The first reallocations within the national budgets in favour of R&D expenditure could result in a rise in employment – at first in this sector, later in the entire economy – and could at the same time accelerate growth.

Against this background, the growth model of the European Union promoted to date should be critically scrutinized. In the past, greatest attention was paid to the savings and investment rates of the member states. In contrast, investments in education, research and development have been neglected in past decades. In contrast, the American economy with its lower savings and investment rates but higher expenditure for education and research and more funds for the development of new technologies has higher growth and a higher employment rate. From these trends clear growth, education and technology policy goals can be derived, which are necessary for a successful implementation of the Lisbon process.

From the first interim reports on the Lisbon process, the conclusion can be drawn that the European Commission has cut back its goals with respect to the Lisbon Strategy. The core strategy of making the EU the most competitive area in the world by the year 2010 has been dropped from the proposal put forward in February 2005 for a "renewed" agenda. In the same way, the authority has dissociated itself from the target of raising the employment level to 70 per cent by 2010. In order to get the Lisbon Agenda back on its feet again, the Commission and member states will now present so-called Lisbon action plans where they outline concrete steps that could raise EU growth and which would be tied to a clear time schedule.

In order to firm up their goals, the European Union has developed a group of indicators to examine and analyse the individual member states' research policies in more detail in the course of a so-called "benchmarking process" (see figure 10 and 11). The research policy of the member states is to be examined with the aid of this process on the basis of four key topics with the corresponding indicators. This involves the following four topics:

- Human resources in the R&D sector including the attractiveness of scientific and technical careers,
- Public and private investment in the R&D sector,
- Productivity in the science and technology sector, as well as
- Impacts of R&D on economic competitiveness and employment.

Making use of this first group of indicators, in the following a broad, comparative survey will be made of the performance of the member states with respect to the four above-mentioned topics on the basis of the available, internationally harmonized statistical data. As far as possible, comparative indicators should be taken into consideration for the USA and Japan.

In connection with research policy in the individual countries, benchmarking is an instrument that can be used to increase the performance of the respective country by improved policy making and adoption of best practice. Benchmarking opens up the opportunity for learning
and encourages the application of new solutions and procedures in research policy. The benchmarking methodology involves performing analyses and measurements in two stages, thus creating the basis for an improved policy implementation.

<table>
<thead>
<tr>
<th>Total R&amp;D expenditure per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of researchers per capita</td>
</tr>
<tr>
<td>New S&amp;T PhDs per capita</td>
</tr>
<tr>
<td>Total education spending per capita</td>
</tr>
<tr>
<td>Life-long learning</td>
</tr>
<tr>
<td>E-government</td>
</tr>
<tr>
<td>Gross fixed capital formation</td>
</tr>
</tbody>
</table>

Figure 10: The different subindicators describing the main indicator of investment in the knowledge-based economy

<table>
<thead>
<tr>
<th>GDP per hours worked</th>
</tr>
</thead>
<tbody>
<tr>
<td>European and US patents per capita</td>
</tr>
<tr>
<td>Scientific publications per capita</td>
</tr>
<tr>
<td>E-commerce</td>
</tr>
<tr>
<td>Schooling success rate</td>
</tr>
</tbody>
</table>

Figure 11: The different subindicators describing the main indicator of performance in the knowledge-based economy

For a more precise classification and for a comparison of the individual performance of the member states of the European Union in the fields of research and development and of innovations, so-called subindicators were compiled as a complement, enabling precise comparability of the values obtained in the individual EU member states. Particular attention will be paid to financial resources and their characteristics by including the indicator "investment in the knowledge-based economy" and the indicator "performance in the knowledge-based economy" as two important individual indicators.

7. Summary

Publicly funded energy research needs structures that promote efficient and successful work at universities and research institutions. To this end, the following stimulus must be given:

- Subsuming all responsibilities for energy research in one ministry (national) or one EU department,
- Improved coordination of energy research on the various levels (EU, nation-state, federal states),
- Focusing all energy research activities on one well-structured programme,
- Concentration on internationally competitive institutes and universities,
- Orientation and reflection of national energy research in EU programmes and global initiatives,
- Structuring the content of energy research according to sectors or services,
- Medium- to long-term orientation,
Close dovetailing of government basic research with industrial research and commercial product development (market launch), and

Improving financial resources.

Whereas the task of privately funded energy research is to contribute to product development and thus to increase the competitiveness of the company, the job of research financed by public funds is to lay the national foundations for these types of innovation processes and thus to create national siting advantages for international competition. In the age of globalization, government-funded energy research also has the function of maintaining know-how in a society irrespective of the interests of individual companies.

The expenditure and effort required to organize science has increased significantly in past years. Present research policy, both on a national and also an EU level, seems to proceed from the paradigm that innovation is only a question of organization. A glance at historical events will, however, show that innovation – especially basic innovations – is to an at least equal extent the result of motivation and commitment by individual scientists.

References


Risø-R-1517(EN) 331


Creating a vision for the future. Long-term R&D on a short sighted electricity market

By Peter Markussen, Elsam (ptm@elsam.com), and Lotte Darsø, Learning Lab Denmark (lotte@lld.dk)

Abstract

Historically well-established networks among the politicians, power companies, industry, and research institutions have with success dominated innovation in the energy sector. As a consequence of the liberalization in the late 90s, long-term investments have been reduced and because of the increased competition R&D in power companies around Europe is dominated by short-term projects focusing on technological performance and efficiency of the power stations.

The energy sector is, however, still faced with long-term problems such as security of supply, environmental responsibilities and economic performance, and these challenges demand new solutions, which, in our opinion, should be obtained through collaboration and co-creation. This calls for social innovation based on new types of relations between research institutions, politicians and the energy supply sector.

Thus the goals of this paper are to: 1) suggest a project phase (Darsø, 2001), where it is possible and legitimate for the stakeholders to discuss long-term visions that encompass a diversity of technologies, and 2) use scenario techniques as tools for conceptualizing and prototyping this vision.

The main question is: How can we create a long-term vision for the Danish energy system that is meaningful to multiple stakeholders?

1 The challenge

The energy sector is faced with a number of challenges such as security of supply, environmental aspects and demands for efficient energy production. In a historic perspective, the energy sector has solved these challenges through technological development in well-established networks among authorities, research institutions, industry, and energy supply companies.

The liberalisation of the energy sector in the 90s changed the division of responsibility in the energy supply chain. Only very few market actors have size and influence on the energy supply chain through vertical integration to take on the risk connected with
technological development or larger investments. The result is, that R&D funds are either reduced or an increasing amount is spent on short-term efficiency projects.

To solve future challenges a common long-term vision is needed. The vision must be meaningful to all actors in the energy sector and should be regarded as sound enough for making long-term investments. To develop a new vision it is necessary to re-establish existing relations in the energy sector and focus on the future challenges. The re-establishing has been described under the name of Triple Helix signalling that the cooperation between industry, society and research institutions is the driving innovation force. (Risø, 2002, 7).

In the following we will argue that this re-establishing of relations can be seen as the foundation for a social innovation process. The term social innovation was coined by Peter Drucker (1985:126) to describe innovation that arises from social needs rather than from technology. It concerns new approaches, functions and constellations of social interaction. Social innovation builds on human ‘technology’ and is often accentuated by the creation of new concepts. The conditions for creating social innovation are that the interested parties are deeply motivated for making a difference and that they regard change as a possibility for renewal. With the Danish energy sector as the empirical case study this article will try to describe how the triple helix can be a true innovation force and create not only new innovative technologies but also an innovative capacity for meeting large changes in the global framework of the energy sector. This article alleges that the present groups in the Danish energy sector still focus on historic relations characterised by the protection of own interests and based on existing knowledge, which means that the aim of participation is to influence the final result and not to create new knowledge.

The authors recommend the scenario technique for improving existing relations and for creating and acknowledging the consequences of the current change and thus focus on possibilities instead of risks associated with the change. This leads to the following question:

How can we create a long-term vision for the Danish energy system that is meaningful to multiple stakeholders?

The first part of this paper describes the concept of the preject phase and the use of scenario techniques. The second part is an assessment of the capacity for social innovation in the existing relations in the Danish energy sector. The remainder provides some general recommendations and perspectives for further action.

2 The preject and the innovation process

The following builds on Darso’s research (Darsø, 2001) on the early phases of innovation. Her question was: In what ways can innovative processes be initiated, supported and managed towards innovative crystallization in heterogeneous groups?
The early phases of innovation are different from a project. The common definition of a project as a unique, goal directed, time limited, cross-organizational enterprise, which can be planned and evaluated, does not fit the early innovation process, which is open-ended, goal seeking and geared towards identifying and framing problems. In order to describe the process that precedes a project a new term, the preject, was evoked. The Diamond of Innovation is a dynamic framework for describing the preject, which displays four dimensions that are important for a successful innovation process: Knowledge and ignorance; relations and concepts.

**Knowledge:** Not surprisingly knowledge is necessary for innovation, but knowledge has many dimensions and develops constantly. Knowledge can comprise factual knowledge, based on data, as well as personal knowledge, based on experience. The surprise is that quite often knowledge becomes more of a barrier than a support, because existing (habitual) knowledge often lock people’s thoughts and prevent them from thinking in new directions. Much innovation is built on not knowing that things cannot be done.

**Ignorance:** Interestingly, accessing what we do not know is paramount for innovation. There are several layers of ignorance. First there are the things we know that we do not know. Secondly there is the ignorance we are not aware of, and finally there are the thoughts and possibilities that we could not even imagine. The challenge lies in the fact that working with ignorance is threatening to most people. Focusing on knowledge feels both easier and safer. When you admit what you do not know, you will be exposing yourself and become vulnerable, but according to Darso’s findings, it is in the arena of ignorance that the new is born.

**Relations:** The quality of relations is the building block for innovation. Relations are tacit and form during conversation. If relations are competitive and permeated by underlying power games, innovation will generally not happen. Innovation is much more bound to happen if the participants start the preject by building ‘common ground’ and consciously form relations of trust and respect. In that case the participants have more courage to access what they do not know and thereby enhancing their chances of innovative crystallization.

**Concepts:** When groups want to innovate, they present thoughts and ideas to each other, discuss, ask questions and use many words. Words and talking are, however, not enough, when new concepts are desired. It can therefore enhance communication tremendously, if people try to use other forms of expressions, such as drawings, prototypes and visualizations, as well as images, metaphors and scenarios.

The Diamond of Innovation is a framework for improving communication and for building and enhancing mutual understanding of innovation processes in groups. It can serve in clarifying visions and expectations for the preject (Darso, 2001: 352). It is originally derived from findings on heterogeneous project groups in a pharmaceutical company, but the purpose of this paper is to propose that this framework be applied to create Triple Helix Innovation between companies, authorities and research institutions.
of the energy sector. Darsø’s point is that the potential of innovation exists in heterogeneous groups because of the differences, but only if the group starts by building common ground through systematic and structured communication. We believe that common ground can be created by working with scenarios.

3 Scenarios as a tool to promote innovation

Scenarios are feasible, consistent and coherent illustrations of the future and their purpose is to structure the uncertainty in an increasingly complex and changing world. On one hand scenarios create structure when they are being used to evaluate strategic considerations and on the other hand scenarios create a process for providing a common understanding of problems and relations by the persons participating in the preparation of the scenarios. Thus the scenario process contributes to provide the common basis for decision, which the strategic considerations take as their starting point.

Elsam A/S has developed the scenario technique used here for both internal and external use in the knowledge-sharing forum Energy Together (Energy Together, 2005).

Elsam’s scenario method originates from the dialogue based scenario process (iff, 2004). Normally scenario techniques are used by small stable groups. Thus, when using the technique at society level, it is important to have in mind that many parties with varying representatives need to feel ownership towards the knowledge produced. To make the method suitable for a project phase at a society level, the focus must be on the creation of relations and the formulation of the problem. The scenario technique’s social dimension is used to improve the relations toward common ground and knowledge sharing by involving ignorance, knowledge and concepts.

3.1 Relations

Countless conferences, seminars and informal meetings are held within all kinds of sectors. This creates a network between the actors and a mutual knowledge, which helps create a good atmosphere. These arrangements often include professional contributions and exchange of information, but rarely become actual knowledge sharing. The reason for this is that the organizers set the problem and there is no follow up on the knowledge created.

It is important to start each meeting with a preject phase, where all participants explain their expectations, their interests for participating and which role they intend to play in the process.

Before starting discussions the formulation of the challenge to be discussed should be agreed upon to ensure a focused dialogue. The challenge formulation should also include an assessment of when the challenge has been overcome. In larger groups this may not be possible, but then at least the organizers should make their intentions clear for the attendants.
3.2 Ignorance

In the dialogue between contrary attitudes and between new actors, ignorance is laid open and new knowledge is created. This happens through a joint identification of uncertainties, categorized according to decision level and degree of influence on the energy sector. It is further estimated whether these uncertainties can be influenced or not by the participants as a group.

Wild cards are uncertainties that can change the existing trends. This category is helpful in establishing agreement on, what the current trends actually are.

The estimation of whether the uncertainties can be influenced will often be subjective. The discussion of influence thus helps clarify who can handle a given risk and thus reduce the total risk of the group. This corresponds to the argumentation for risk assessment in the financial portfolio theory.

Figure 1. Perception map for uncertainties

After this the most important and “hard-to-influence” uncertainties are selected for further analysis. The purpose of the analysis is to establish whether the uncertainties are important and under which preconditions. If there is disagreement on the importance of an uncertainty the knowledge-dimension (in the form of analysis) will help determine its influence on the energy sector.

3.3 Knowledge

The uncertainties are analyzed with both quantitative and qualitative models. As the analyses are the building blocks of the scenarios, they need to be consistent. By comparing the chosen uncertainties and their mutual influence it is possible to set up an arena of uncertainty.
The energy sector has a number of representations, modelling the energy market and the energy system. The input to the models is often the same and knowledge sharing would be advantageous. At the same time it would further a constructive dialogue on the questions, which the models can answer instead of accusations on wrong assumptions and input data.

For the qualitative part, knowledge from the individual parties on the functionality and strategies of the energy markets form the framework for the scenarios. The uncertainty arenas are combined in scenarios, which can be used to evaluate the consequences of action and to identify the most robust strategy and vision.

We recommend developing three scenarios. The first scenario should be based on the existing trends. The two other scenarios on a change in the trends, where the decision level for the challenge discussed is either moved to a higher or lower level of decision.

3.4 Concepts

The identification of uncertainty arenas and the use of pictures, figures and facts in developing the scenarios assure that the actors create a common interpretation of these, based on the individual uncertainties. The sharing of knowledge builds common ground and helps maintaining the knowledge produced.

The new knowledge gained through the scenario process eliminates some uncertainties, puts forward others and changes the possibility for influence. This gives a more detailed picture of the total risk for the group, which can form basis for the ongoing dialogue.

The innovation process is iterative, but the use of scenarios enables a much deeper communication and at the same time secures that the knowledge produced is easily accessible for the next meetings. This ensures the continuous development of new and better relations between the parties and paves the road towards a shared vision for a long-term strategy.

4 A common vision as an innovation process

During recent years, many initiatives have been made in Denmark to boost the cooperation between industry, society and research within the energy sector.

In the following, the characteristics of five of these initiatives will be compared to the four dimensions of the project and their group efficiency potential to overcome own interests will be evaluated on the basis of available material. In the evaluation of the initiatives it is important to have in mind that their main purpose are not be to create social innovation.
The first initiative is the Energy Camp (Energy Camp, 2005) arranged by the Association of Danish Energy Companies, Danish Wind Industry Association, The Danish Society of Engineers, Danish District Heating Association, and Dansk Metal. The idea is a 48-hour camp to develop visions for the Danish Energy Sector. The plan is to repeat the camp annually. The initiative focuses on relations and knowledge in the Innovation Diamond.

The second initiative is from The Danish Board of Technology (Teknologirådet, 2005). The goal is to establish an interactive process with the Danish politicians on energy issues through a number of public hearings. Again focus is on relations and knowledge from the Innovation Diamond.

The third initiative is a new Energy Action Plan to 2025 (Energistyrelsen, 2004) initiated by the Danish Parliament and the Danish Energy Authority is responsible. The purpose is to describe the current challenges for the Danish energy supply and concrete actions for the future. The development of an Energy Action Plan is usually done with a 5-8 years interval and the plans include detailed analysis. Focus is on concepts and knowledge.

The fourth initiative is the annual System Reports made by the two Danish Transmission System Operators (Eltra, 2004 og Elkraft System, 2004). The System Reports are a part of their tasks according to the Danish Electricity Supply Act and can therefore also be described as a well-known concept with detailed analysis.

The fifth initiative is the establishment of a Danish Energy Industry Association (DI, 2005) for Danish industries directly or indirectly involved with energy matters. The Association has as its purpose to promote the Danish Energy Industry and focus is on relations and exploration of new ideas.

To sum up none of the present initiatives have deliberately worked with all four of the recommended dimensions from the Innovation Diamond. If the initiatives are combined, all four dimensions are covered; however over-represented by relations, concepts and knowledge.

This may not be a problem, if the initiatives have the characteristics of high group efficiency and are able to cope with historic relations and own interests.

The evaluation of the group efficiency is based on the terminology developed in the Innovation Diamond (Darsø, 2003: 348). Depending on the group size, history of the group, organizational affiliation, diversity, time span, leadership and purpose of the project, it is possible to evaluate the group efficiency. Smaller groups, with an existing history, external relations, a shorter timespan, shared leadership and an explorative purpose has the best potential to develop social innovation. The evaluation of the five initiatives is described in table 1.
Table 1: Evaluation of the group efficiency and innovative capacity

<table>
<thead>
<tr>
<th>Group size (number of org. Represented)</th>
<th>Group history</th>
<th>Organizational affiliation</th>
<th>Diversity</th>
<th>Time span</th>
<th>Leadership</th>
<th>Purpose/target</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Camp</td>
<td>48</td>
<td>Both existing and new relations</td>
<td>External relations</td>
<td>On guard</td>
<td>Mainly perceived diversity</td>
<td>48 hours (repeated annually)</td>
<td>Pooled leadership</td>
</tr>
<tr>
<td>The Danish Board of Technology</td>
<td>Internal politics</td>
<td>Existing</td>
<td>External relations</td>
<td>On guard</td>
<td>Mainly perceived diversity</td>
<td>2 years</td>
<td>Steering group</td>
</tr>
<tr>
<td>Energy Action Plan</td>
<td>1</td>
<td>Existing</td>
<td>Internal relations</td>
<td>7</td>
<td>1 year</td>
<td>One appointed leader</td>
<td>Explorative search</td>
</tr>
<tr>
<td>System Reports</td>
<td>1</td>
<td>Existing</td>
<td>Internal relations</td>
<td>7</td>
<td>Annually</td>
<td>One appointed leader</td>
<td>Routines</td>
</tr>
<tr>
<td>Danish Energy Industri Association</td>
<td>15-20</td>
<td>Existing</td>
<td>External relations</td>
<td>Smooth in group</td>
<td>Perceived similarity</td>
<td>Continuous</td>
<td>Pooled leadership</td>
</tr>
</tbody>
</table>

All the initiatives have slight or moderate group efficiency and the protection of own interests is a potential threat for the social innovation in the groups. According to the characteristics The Energy Camp and the Danish Energy Industry Association have the largest potential far developing social innovation as a consequence of their new relations and their explorative purpose, respectively.

To conclude the current initiatives to create common ground cannot by them self create social innovation. But if they are linked and sharing of knowledge through cross memberships and interaction all the four dimensions are represented and the potential for social innovation is there.

5 Recommendations

The above analysis shows that at society level the innovation capacity of the present relations may be reduced by the protection of own interests and existing knowledge. At the same time it also reveals that the time pressure is an important factor in defining a vision. All three characteristics reduce the possibility for social innovation. Obviously, this matter is urgent. We therefore recommend starting a CoLLab (Collaborative Learning Lab) in order to overcome these barriers and identify new approaches towards Triple Helix innovation.

5.1 CoLLab

Our recommendation is to establish a Collaborative Learning Lab that includes the major energy sector stakeholders and possibly some new actors to inject new perspectives (e.g. agriculture, art, culture and design, computer science, new media and biotechnology). A Collaborative Learning Lab is an experimental and experiential learning vehicle, a problem-solving tool and a research methodology. The method has been devised at Learning Lab Denmark by the research consortium The Creative Alliance in order to explore relevant business challenges such as creativity and innovation, complex problem solving, organisational change, leadership, etc. The idea is to invite people to become co-researchers of their own learning process and thereby create specific tools and processes that can help each partner develop the new talents, skills and tools needed for social
innovation. In this specific case the suggestion is an experimental setting for creating a long-term vision for the future of the energy sector by applying the Diamond of Innovation as a framework and scenario techniques as the tool. The process will be facilitated and supported by a team of skilled researchers/consultants and documented in order to enable others besides the involved participants to learn from it.

We recommend that the scenario technique be used to cope with the protection of own interests and maintain the knowledge produced to secure common ground and knowledge sharing among the initiatives. The scenario technique can be applied both in the individual groups and for establishing new groups such as Energy Forum. The scenario technique can build common ground by re-establishing the existing relations with new actors and by sharing knowledge as well as ignorance through shared images of the actors’ present perception of the world and the challenges facing them.

From the 70s till now, the grass root organizations played an important role by emphasizing ignorance. It can be argued whether they still play the same role or form part of the historic relations and hold on to the present knowledge. This will not be discussed here.

Most present initiatives emphasize that action be taken now. This applies when it comes to developing new technology, new capacity investment and ensuring the independence of oil before a new energy crisis occurs.

Time pressure, however, tends to reduce the attention given to the problem formulation and pays more attention to achieving a quick definition of the aim.

Consequently it is vital to look at social innovation, not only as a continuous process but also as a condition for ensuring good relations in order to create a sustainable future.

6 Conclusion and perspectives

In Denmark, we already have a tradition for pluralistic decision-making, and the present groups have a long history for using dialogue. And yet there is a need for a structured debate to loosen up the existing structures.

Only when a new world picture based on the present challenges is established will we be able to develop new world pictures and vision to cope with challenges. The current structures and world pictures derive from the energy crisis of the 70s and environmental concerns in the 80s and 90s.

Once the vision is ready, the real project commences, and on its way many persons involved in the development and the implementation phases of the vision will be replaced. This places heavy demands on transferring knowledge from the people behind the vision to the people implementing the vision. Having a precisely formulated problem in a well thought-through vision, makes it much easier to hold the course. If not, the vision will be interpreted in various ways and the implementation will fail.
At the same time the EU plays an increasingly larger role in the formulation of the national energy policy and the globalisation continues. These factors make it obvious that it is important to look outside the Danish borders for actors whose knowledge can contribute to elucidate the Danish ignorance.

Furthermore, the aim of the vision is to create jobs and add value to the Danish society. This strategy will only succeed in a liberal and global market by focusing on IPR - not only on technology but also on business models.

References:

The Danish Energy Industry Association, www.di.dk
Darso Lotte (2001), Innovation in the Making, Samfundslitteratur
Peter F. Drucker (1985), Innovation and Entrepreneurship, Pan Books
Energy Camp, www.energycamp.dk
Energytogether (2005), www.energytogether.org
Risø (2002), Risø Årsberetning, http://www.risoe.dk/rispubl/Aarsberetning/ris-r-1409_dk.htm
Teknologirådet (2004), The future Danish energy system, The Danish Board of Technology, www.tekno.dk
Session 13 – Emerging and Advanced Energy Technologies

Chairman: Allan Schrøder Pedersen, Risø National Laboratory, Denmark
Status on Advanced Coal-Firing

Presented by
Chief Engineer, M. Sc. Sven Kjaer, Elsam Engineering, DK-Fredericia
Sales Manager, M. Sc. Hans Henrik Poulsen, Burmeister and Wain Energy, DK-Gentofte

Abstract
At present Europe is leading the development of conventional supercritical coal-fired power technology world-wide. This success is partly based on a number of advanced Danish SC and USC power plant and the joint European development and demonstration efforts shortly named AD700 and this technology will be reviewed. Also Danish efforts to establish European USC technology in China will be presented followed by an outlook.

1. Introduction
After the energy crisis's during the 1970s and emerging problems to get public acceptance of nuclear power, the power generators renewed their interest in coal as a base fuel for power generation. Major reasons were:

- Coal is the most abundant fossil fuel on Earth with reserves for more than 200 years
- Coal is widely distributed on earth, which guarantee security of supply and competitive prices

Among the power generation technologies focus was on conventional pulverised coal-fired (PF) technology, IGCC and PFBC. However, the operating experiences from a number of IGCC and PFBC demonstration installations did not bring a breakthrough for any of these technologies and confirmed the power generators in their belief in further phased development of conventional extremely well proven PF technology.

AD700 technology is a key technology to Elsam's visions on Venzin.

In Europe, Elsam was a prime driver to draw attention to the potential of supercritical PF technology based on the 9% Cr steel, and in 1997 and 1998 Elsam commissioned the first European 400 MW ultra supercritical (USC) units at the Skaerbaek and Nordjylland power stations. The two units were based on P91 for thick-walled headers and steam lines and steel E for the HP and IP turbines.
Similarly, the German lignite-fired SC and USC power stations Schwarze Pumpe, Boxberg and Lippendorff commissioned in the period 1997-2000 were also based on P91 for the thick-walled components. Table 1 shows steam parameters of these early “P91-installations”.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Comm. year</th>
<th>Net output MW</th>
<th>$P_{\text{Main Steam}}$ bar</th>
<th>$t_{\text{Main Steam}}$ °C</th>
<th>$t_{\text{Reheat Steam}}$ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarze Pumpe</td>
<td>1997+1997</td>
<td>820</td>
<td>268</td>
<td>547</td>
<td>565</td>
</tr>
<tr>
<td>Boxberg</td>
<td>2000</td>
<td>910</td>
<td>266</td>
<td>545</td>
<td>583</td>
</tr>
<tr>
<td>Lippendorf</td>
<td>1999/2000</td>
<td>940</td>
<td>267</td>
<td>554</td>
<td>583</td>
</tr>
<tr>
<td>Skaerbaek</td>
<td>1997</td>
<td>400</td>
<td>290</td>
<td>582</td>
<td>580</td>
</tr>
<tr>
<td>Nordjylland</td>
<td>1998</td>
<td>385</td>
<td>290</td>
<td>582</td>
<td>580</td>
</tr>
</tbody>
</table>

Table 1 Early European “P91 installations”

The 9% Cr steel for thick-walled components have been a great success and opened the way to USC steam parameters in the range of 300 bar and 600 °C and net efficiency in the range of 45-46% for an inland location. We all owe much respect to professor Fujita from the University of Tokyo whose lifelong work with the 9-12% Cr steel opened the way for a revival of the PF technology.

As an outcome from the good operating experiences of the Danish power stations Nordjylland and Skaerbaekvaerket Elsam Engineering supported since 2000 Danish boiler maker Burmeister and Wain Energy A/S (BWE) in establishing European USC technology in China with a net efficiency of +47%.

However, the European industry – both manufacturers and power generators - still wants to continue development of the extremely well proven PF technology through new materials and improve efficiency at competitive cost. Therefore, during a COST meeting in 1994 a group of 40 power generators and manufacturers agreed to investigate if Nickel based alloys (NBA), which were well known from gas turbines and the nuclear programmes (fast breeder) would be good candidates for an advanced technology named AD700. Main and reheat steam temperatures would be raised into the range of 700 °C and main steam pressure into the range of 350-375 bar and net efficiencies of beyond 50% were forecasted.
The Commission’s DG RTD and DG TREN showed strong interest to support the idea agreed to support a phased programme ending up with a full scale demonstration plant as shown in Figure 1. For each phase, an application had to be filled in.

The potential for CO₂ emissions savings from efficiency improvement in the electricity sector is immense in particular if European Power technology would be introduced into the North American market and the surging economies of Asia. Currently much of the installed coal-fired power generation capacity worldwide is operating at less than 30% efficiency. However net efficiency of more than 45% is now economically viable and developments promise to achieve in excess of 50%.

2. AD700 Phase 1. The feasibility studies phase

DG TREN awarded the first contract in 1997 under the 4th Framework Programme (FP4) so that the work could begin in January 1998. The name of the project was “Advanced supercritical PF power plant operating at 700 °C” - or shortly AD700 - and 40 partners from 13 countries joined this large European R&D project co-ordinated by Elsam Engineering.

![Figure 1](image_url)

**Figure 1**  Time schedule for development of the AD700 technology

The contract covered development of new materials, improved designs and investigations on the economic viability of AD700 technology.

Developments of new materials covered:
• Development and start of long term demonstration of Nickel based alloys for those sections of the water/steam cycle, which operate at steam temperatures beyond 650°C. This means final super and reheaters, final headers, hot steam lines, turbine valves, inlet section of the turbine casings and finally the rotors.

• Development and primary demonstration of austenitic steel for those sections of the super and reheaters, which operate in the steam temperature window 600-650 °C. In particular development of good austenitic steel was important to enhance the use of austenite as much as possible, thereby saving extremely expensive Nickel based alloys.

• Development and primary demonstration of martensitic steel for headers and interconnecting steam lines which operate in the steam temperature window 600-650 °C.

Target for 100,000 hours creep strength of each material was 100 N/mm² at metal temperatures 750 °C for the nickel based alloys, 700 °C for the austenite and 650 °C for the martensites.

Within the AD700 project two new boiler tube materials, NBA 740 from Special Metals and the austenitic steel from Sandvik named SANICRO25, have been successfully prequalified but the project has failed concerning development of new martensitic steel. However, new attempts are being made within the COST programme and with the same target as for AD700.

Concerning thick walled steam lines and outlet headers will be developed within the AD700 project the AD700 project chose an existing very promising precipitation hardening NBA named Nimonic 263 with an extremely high creep strength. Scottish Wyman Gordon has without problems extruded five meters of main steam line in Nimonic 263 from an ingot made by Special Metals but all NBA’s are hard and very difficult to e.g. machine, cut and drill. Therefore many investigations and tests to define the optimum manufacturing route are still outstanding.

A selection of the $10^5$ hour creep strength of a selection of AD700 materials for boiler tubes for furnace walls and super heaters and for thick walled steam lines are shown in Figure 2. The figure illustrates that target values concerning creep strength have been reached except for Inconel 617.
NBAs 617 and 625 are the main candidates for valve bodies, casings and rotors for HP and IP turbines and test valve bodies and casings have been casted. Similarly test rotors have been forged and tested. For turbine blades and bolts Waspalloy has been demonstrated.

Development of new designs mainly covered:

- Investigations on furnace wall design and design/selection of materials for super and reheaters.
- Investigations on design of turbine casings and rotors to minimise the use of nickel based material.
- Investigations on the potential of savings through a revised overall architecture of the power plant named “Compact Design” to shorten the length of steam lines. Also revised boiler designs with outlet headers close to the turbine were investigated.
- Cost/benefit analyses of the economic viability of the AD700 technology.
Phase 1 was planned to stop by the end of 2003 but has been extended by one year to complete some of the material demonstrations. The budget for phase 1 is 20 million Euros with 40% co-funding from DG TREN.

3. AD700 Phase 2. The preparatory work phase

DG RTD awarded the second contract in 1999 under the 5th Framework Programme (FP5) so that work could begin in January 2002. 34 partners from 10 countries joined phase 2 and Elsam Engineering also co-ordinate this phase.

The phase 2 contract covered:

- Demonstration of fabricability and manufacturing of new materials from phase 1
- Demonstration and in-plant testing of new materials from phase 1
- Turbine component prototype manufacture and test
- Preparatory component design
- Preparatory work for phase 3, the component demonstration phase: Defining the test facility and finding a host
- Preparatory work for phase 4, construction of the full-scale demonstration plant: Investigations on a business plan. This work also includes continued investigations on the economic viability of AD700 technology.

In both phases 1 and 2 the economic viability of the AD700 technology has been controlled thoroughly through comparison with a well proven world market supercritical technology with 250 bar/540/560 °C in phase 1 and with a state of the art technology like the “Referenzkraftwerk Nord Rhein Westphalen” with 300 bar/600/620 °C in phase 2. In both cases it came out that the cost of electricity is the lowest for the AD700 technology, but the investigations also clearly demonstrated that the additional costs of the boiler are highly dependent on the materials available and to a lower degree if the designers succeed with their “compact design” philosophy. If the material developers succeed with their present development work the economic viability of the AD700 technology seems well secured.

It is important to note that the FP5 co-funded phase 2 NBA material programme has been co-ordinated with the MARCKO programme since the start of phase 2. This means that information on development of the different nickel based alloys is exchanged between the two groups, so one can say that a small ERA network already exists in the field of NBA’s.
Phase 2 is planned to stop by the end of 2005 but a two year extension will be applied for. The budget for phase 2 is 11 million Euros with a 50% co-funding from DG RTD.

4. AD700 Phase 3. The component demonstration phase

Phase 3 is now well established but it was a difficult phase to start, and several attempts have been made to establish a test facility. Basic to the final success of establishing phase 3 was the positive signal from a group of nine major European power generators (EdF, Electrabel, Elsam Kraft, EnBW Kraftwerke, Energi E2, E.ON Energie, RWE Power, Public Power Corporation, Vattenfall Europe) named the E-max group that they were willing to share the cost of a test facility with the Commission. However, for all phases the E-max group consider an economic commitment from the Commission to be paramount as the economic commitment is also being considered to be a political approval.

The first proposal for an AD700 test facility targeted a full scale demonstration of furnace walls, superheater, steam lines with HP bypass and safety valves and one HP turbine from each of the turbine makers Alstom and Siemens. In this test facility all major components of the water/steam cycle would have been demonstrated in full scale and it would have shortened the time to commercial introduction of the AD700 technology by some five years. Planned mother plant was unit 3 at Skaerbaekvaerket but the full scale test facility failed due to an unexpected lack of support for fossil fuel based technologies in the Commission’s FP6 programme.

Despite of missing support for fossil fuels in the FP6 programmes the E-max group and the manufacturers succeeded with an application named COMTES700 to the Commission’s Research Fund for Coal and Steel (RFCS) for a medium sized component test facility (CTF) to be established at the E.ON power station Scholven, unit F. Except for the turbines, the CTF contains the same components as the full scale test facility but in a smaller scale. The CTF will operate at temperatures up to 700 °C and starts operation by the end of June 2005 and the following materials will be tested for their oxidation and corrosion behaviour:

<table>
<thead>
<tr>
<th>Component</th>
<th>Steel</th>
<th>NBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace walls</td>
<td>T24, HCM12</td>
<td>617 (fall back option)</td>
</tr>
<tr>
<td>Superheaters</td>
<td>HR3C, SANICRO25, DMV310N</td>
<td>617, 740</td>
</tr>
<tr>
<td>Thick-walled sections</td>
<td>NBA: 617</td>
<td></td>
</tr>
</tbody>
</table>
The industrial partners of COMTES700 are Alstom Power Boiler, Babcock-Hitachi Europe, Burmeister and Wain Energy and Siemens. The budget of the CTF is 15 million Euros with 40% co-funding from the RFCS. Operation of the CTF is planned for four years and VGB PowerTech co-ordinates the efforts.

Additionally a joint Siemens/Alstom turbine valve in NBA 625 will be installed in the CTF but demonstration of a turbine will be missing.

In parallel with the CTF, a small test rig (ETR) is now operating in the boiler of Elsam’s Esbjerg Power Station at steam temperatures up to 720 °C. The advantages of the ETR are a higher resolution of the oxidation and high temperature corrosion phenomena than in the CTF and gaining of experience from one boiler more. The test rig will be paid fully by the Eemax Group and the operating time is planned for four years.

At the Esbjerg Test Rig the following superheater materials are being tested:

Austenite: TP347HFG, HR3C, SANICRO25,
NBA: HR6W, 617, 740

5. AD700 Phases 4, 5 and 6. The Full Scale Demonstration Plant and its operation
The overall time schedule indicates that phase 4 which covers planning and construction of the Full Scale Demonstration Plant (FSDP) would begin in 2008 and last four years. However, depending on the results of phase 3, the starting date of phase 4 might move into 2009. The final phases 5 and 6 will be a three-year period of operation of the FSDP with operation of the FSDP and feedback of experience to the partners, so that the AD700 technology will be commercially available around 2014 after a development period of 20 years. The output of the FSDP is planned to be in the range of 400 MW.

6. Frame Work 7 Programme
The construction of a FSDP will be a big challenge to the industry and without a positive dialogue with the Commission it will be difficult to find partners. Therefore, the recent positive attitude towards expressed by the Commissioner for Energy Mr Piebalgs and the ongoing efforts to establish a Technology Platform (TP) which should act as an advisory group for the Commission concerning “high efficient zero emission power plant” are very encouraging.
7. Danish efforts to establish European USC technology in China

The leading position of Denmark in Ultra Super Critical (USC) power plant technology has been noticed worldwide. During the last 5 years the world’s potentially largest energy consumer: Peoples Republic of China has shown their interest in the Danish developed Ultra Super Critical power plant technology.

Starting with a general feasibility study on USC steam cycles in cooperation with China Power Engineering Consulting Corporation (CPECC) in 2000, BWE has developed their activities in China in the last couple of years. In 2003 a study on 640MWe single reheat USC power stations were handed over to CPECC and on the 26. February 2004 a memorandum of understanding between BWE, Chinese generator Luneng and the Chinese company Dragon Power Ltd. on USC technology was signed in the great hall of the peoples.

The goal of this memorandum is to enable Chinese companies to erect USC power stations in China using the Danish USC power plants as master models. In connection with this agreement a stepwise transfer of Danish USC boiler technology from BWE to Dragon Power will be for seen. However for the first units to be build the engineering package planned to be handled by BWE will almost correspond to the normal architect engineers’ scope of work.

Already a project has materialised namely the “Lanshan Rizhao Demonstration Power Plant”. Due to the Chinese political recognition of this project a very ambitious time schedule has been put forward:

Authority approval is expected in only 6 months and design, manufacturing and erection will be completed in only 42 months. The power plant consisting of 4x660MWe USC units will be located in Lanshan in the Shandong province.

In order to obtain high plant efficiency standard the design principles used in Denmark is applied. By exceeding the steam parameters from the newest Danish USC power Plants Avedøre # 2 (see table 2) an overall plant efficiency of more than 47% is expected.

**Table 2. USC steam parameters of Danish and Chinese plant.**

<table>
<thead>
<tr>
<th>Boiler</th>
<th>Avedøre # 2</th>
<th>Lanshan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Water Temperature</td>
<td>°C</td>
<td>320</td>
</tr>
<tr>
<td>Live steam pressure</td>
<td>barg</td>
<td>305</td>
</tr>
<tr>
<td>Live steam temperature</td>
<td>°C</td>
<td>580</td>
</tr>
<tr>
<td>Reheat steam pressure</td>
<td>barg</td>
<td>70</td>
</tr>
<tr>
<td>Reheat steam temperature</td>
<td>°C</td>
<td>600</td>
</tr>
<tr>
<td>Condenser pressure</td>
<td>mbar</td>
<td>24</td>
</tr>
<tr>
<td>Plant efficiency (on coal)</td>
<td>%</td>
<td>47</td>
</tr>
</tbody>
</table>
Exceeding the average Chinese plant efficiency of 40% by 7% points a reduction of the CO2 emission of app. 425Mio t/year/unit can be obtained. In this perspective the Danish USC technology can therefore be seen as a Clean Coal technology.

8. Outlook
Concerns about global warming mean that, at least in the OECD area, continued use of fossil fuels will be part of an overall carbon management strategy. This is already being taken on board within National Programmes, e.g. the German COORETEC initiative and the emerging UK strategy on Carbon Abatement Technologies (CATs). These initiatives recognize the importance and merit of the “twin trajectory” approach to fossil fuels RD&D. Within this approach, two research paths are pursued in parallel. Firstly the ongoing drive for efficiency improvement on existing and emerging power generation technologies and secondly the commercial development of acceptable cost options for carbon dioxide capture and storage or re-use.

The ongoing AD700 works have successfully demonstrated that the technology is feasible and economic viable. But it is important to continue work on improvements of NBA’s to achieve reductions of materials and manufacturing cost and on reductions of boiler cost.

At present it looks like the Commission will include fossil fuels into FP7 and focus on the establishment of “light house” projects. Therefore, with an adequate support from FP7 the start of building an FSDP based on AD700 technology with CO2 capture and storage or re-use seems possible within 4-5 years.

Through establishment of European high efficient USC technology now and later on introducing AD700 technology into the surging economies of Asia the potential for CO2 savings is immense and should be better recognised in future.
Progress of dye sensitized solar cells at Danish Technological Institute

Hanne Lauritzen and Peter Poulsen, Danish Technological Institute, PEC-Group Gregersensvej 1, 2630, Denmark
E-mail: hanne.lauritzen@teknologisk.dk
E-mail: peter.poulsen@teknologisk.dk

Abstract
Dye sensitized solar cells have been constructed having and overall efficiency of 7.3 % under 10 mW/cm² and 6.6 % at 100 mW/cm² simulated sunlight (equivalent to respectively 0.1 and 1 sun at AM 1.5). Equipment for spatial photocurrent distribution monitoring of solar cells is established and measurements on the produced cells shows a profile in the current draw being larger at the edges than in the center of the electrode.

Keywords: Dye sensitized solar cells; Imaging techniques;

1. Introduction
Due to the rapid depletion of fossil fuels bringing along serious environmental problems much attention has been drawn to developing renewable energy sources for the growing energy demands. One environmentally friendly source is solar cells utilizing the solar radiation to make electricity directly. In this field the conventional inorganic photovoltaic devices have been dominating the marked for half a century. A high efficient low cost alternative to the tradition solar cells is an electrochemical based type called dye sensitized solar cells (DSSC) which have been developed quickly in the past decade since the break through report in 1991 by Prof. Michael Grätzel and B. O’Reagan.¹ Values exceeding 10% efficiency at 1 sun illumination (AM1.5) have been reached.² This type of solar cell has many advantages to the inorganic ones for example they can be made transparent and in different colours which makes them attractive for architectural applications as a building integration component. A purple transparent cell made at the Danish Technological Institute is showed below on figure 1.

Fig. 1
Dye sensitized solar cell made at Danish Technological Institute

In Denmark most work done on this field is governed by Danish Polymer Center at RISØ National Laboratory in Roskilde and Danish Technological Institute in Taastrup. Focus is on creating new opportunities for Danish Industry to be players on this new promising segment of the solar cell marked. In the group on Danish Technological Institute architects are studying the use of solar cells as and
building integrated component giving an added value to the building as for example a window being able to produce electricity while still being transparent and even giving sunshade when the sun is high. A designer is working at the institute on integrating solar cells in mobile applications giving for example the consumer the possibility to charge mobile phones while hiking.

The working principle of the DSSC is shown below in figure 2.

![Fig. 2. Working principle of DSSC.](image)

When a dye molecule is hit by a photon from the sun an electron is excited bringing the dye to a higher energy level ($S^*$). The electron is injected into the conduction band of the semi conducting TiO$_2$ layer bringing about an oxidation of the dye ($S^+$). The oxidized dye is subsequently reduced by an electrolyte containing a redox system R/R’ usually of iodide/triiodide. The electron flows through a transparent conducting layer on a glass electrode and further through and external load to a counter electrode. Here it reduces the redox pair in the electrolyte and the circuit it completed.

### 2. Experimental

#### 2.1 DSSC fabrication

The solar cells consists of two K-glass 27 $\Omega$/ substrates having a transparent conductive oxide (TCO) layer of SnO$_2$:F on one side and an overall light transmission of 85% in the visible light spectrum. At first holes are drilled in the glass used for the counter electrode. Subsequently the glasses are thoroughly washed in a dishwasher added detergents. 500 $\mu$m wide silver lines are plotted on the conducting side of both glass substrates from a thinned Condutrox 3350 Ag Conductor paste (Ferro Corporation) followed by annealing at 520°C for 30 minutes in air. The achieved silver line thickness is around 10 $\mu$m. On the photo electrode a thin dense blocking layer of TiO$_2$ is spin coated from a solution of Ti-isopropoxide in acetylacetone on the TCO glass side. On top of this a highly transparent layer of porous TiO$_2$ is applied by tape casting with a spacer of 50 $\mu$m of a paste called Nanoxide HT (purchased from Solaronix SA) followed by sintering at 450°C in air for 30 minutes. The obtained layer is 4 $\mu$m in thickness and highly transparent. Afterwards a diffuse layer of highly porous TiO$_2$ is deposited by tape casting of Nanoxide D (Solaronix) with a spacer of 100 $\mu$m in thickness followed by annealing at 450°C in air for 30 minutes. The resulting layer is 8 $\mu$m in thickness and diffuses light. The total thickness of the TiO$_2$ layer is therefore 12 $\mu$m. The counter electrode material is deposited by tape casting of a Pt-Catalyst T/SP (Solaronix) paste with a 50 $\mu$m spacer mask and the resulting layer is sintered for 30 minutes in air at 400°C. A schematic draw of the electrode buildup is shown in fig. 3.

![Fig. 3.](image)
Schematic buildup of the electrodes.

Surlyn 1702 polymer foil 50 µm thick (DuPont) was cut in a frame and used as spacer and sealant material for the cell. The electrodes are melted together by the polymer at 160°C for 45 minutes. The dye N719 (Solaronix) with the chemical name cis-bis(isothiocyanato)bis(2,2'-bipyridyl-4,4'-dicarboxylato)-ruthenium(II) bistrabutylammonium in a concentration of 0.5 mM in high-dry-ethanol is flushed through the cell overnight leaving a monolayer of dye adsorbed on the porous TiO₂ layer. The cell is filled with electrolyte consisting of 0.05 M I₂, 0.5 M tert-butyl pyridine, 0.5 M LiI in acetonitrile. The drilled holes are sealed with a microscope cover slide with a melted Surlyn 1702 pearl beneath to avoid leakage of the electrolyte. The finished DSSC solar cell looks as shown in section 1 on fig. 1 and in a different size below on Fig. 4.

Fig. 4.
Picture of finished cell.

2.2 Characterization

I-V characteristics have been recorded by connecting the cells to a Keithley 2400 Source Measure unit while exposing them to light from an Osram XBO 1000 W Xenon short arc lamp. A 4 cm thick water filter was inserted between the lamp and the measuring point to cut out of most IR light. Also a diffuser filter was inserted before the measuring point to diffuse the incident light to resemble natural sunlight mostly. Illumination intensity was 10 mW/cm² and 100 mW/cm² corresponding to respectively 0.1 and 1 sun at AM1.5. The setup is shown on fig. 5.

Fig. 5.
Setup for measuring I-V curves.

To measure the spatial photocurrent response equipment as shown schematically in fig. 6 is build up.

Fig. 6.
Experimental setup for generating photocurrent images.

633 nm laser light is focused and cut off by an aperture leaving a spot size of 100 µm giving the spatial resolution. An x-y stage moves the sample horizontally with a resolution of 1µm. The photocurrent is in the nA region and is amplified 100,000 times before transferred to a data collector and send to a PC generating a photocurrent image of the cell.

3. Results and discussion

Current-voltage characteristics obtained for a cell like the one in fig. 4 having an
active area of 0.5 cm² under illumination by simulated AM 1.5 sunlight at an intensity of 10 mW/cm² is shown below in fig. 7.

Fig. 7.
I-V characteristic for 0.5 cm² cell.

The efficiency is seen to be 7.3 % and the fill factor is 67 %. By illuminating with 100 mW/cm² (1 sun) intensity the efficiency decreases to 6.6 % and the fill factor (ff) decreases to 50 %. The fill factor calculation is shown below, where \( I_{SC} \) and \( U_{OC} \) is respectively the short circuit current and open circuit voltage of the cell under the given illumination.

\[
ff = \frac{\text{max power output}}{I_{SC} \cdot U_{OC}} \cdot 100\%
\]

For the larger electrode areas \( \approx 10 \text{ cm}^2 \) as the one on fig. 1 the efficiency is in the region 3.1-3.7 % (measured from 50 identical fabricated cells) at one sun intensity. At illumination by 0.1 sun the efficiencies are all above 5 %. The decrease in efficiencies when the active area is raised is due to a larger influence of the glass sheet resistance when larger current is drawn from the cell.

Spatial photocurrent characteristics have been done on cells build up as fig 1 and the photocurrent image looks as shown below in fig. 8.

Fig. 8.
Photocurrent image of 10 cm² DSSC.

From the image it can be seen, that more current is drawn from the edge of the cell than from the center. This can be due to current loss in the relatively poor conducting SnO₂:F layer on the glass, where more traveling is done by the electrons through the glass in the center of the cell than at the edges. When fabrication of the TiO₂ electrode layers, edges are usually a little thicker than the middle which allows more dye to be adsorbed on the edges than in the center of the cell which might lead to a higher photocurrent for the edges. The x-y measurement setup has also been used to study micro structured solar cells where transparency is achieved by making a photoanode pattern with transparent spaces between as shown on fig. 9 below of a cell received from Uppsala University in Sweden.

Fig. 9.
Patterned DSSC from Uppsala University.
The solar cell is circular with a diameter of 1 cm and structured by press technique of the photoanode. The photocurrent image is shown below on figure 10.

Fig. 10
Spatial photocurrent distribution of DSSC from Uppsala University.

It is seen from the figures that the photocurrent follows the pattern of the dyed photoanode. The step length of the measurement points is 500 µm which might be too short for measuring all the details of the fine-meshed pattern.

Decay studies by long term outdoor exposure on the institute roof is being done and will be reported later on. The spatial photocurrent analyzing setup will be used to investigate the degradation pattern of the cells.

Projects are going on at the institute to scale up the solar cells to module size by screen printing techniques of all electrode materials. The goal is to construct modules with the same efficiency as the small cells. A sketch of the module buildup is shown below in fig. 11. The progress will be reported later on.

4. Conclusion

In the recent study dye sensitized solar cells have been fabricated by simple tape casting techniques for electrode deposition and the photovoltaic data of cells with 0.5 cm² active area shows efficiencies of 6.6 % and 7.3 % when irradiated by simulated sunlight with an intensity of 10 mW/cm² and 100 mW/cm² respectively (0.1 and 1 sun at AM 1.5). When the same fabrication procedure is followed making cells 20 times larger in area the output of the cells decreases to 5 % and 3.5 % efficiency at the same irradiation intensities. Equipment for monitoring spatial resolution of the photocurrent is established and will be of major importance when studying the degradation of DSSC in the future works.

Acknowledgements

This work has been supported by the Public Service Obligation (PSO) of the Danish Power Utilities. Furthermore authors would like to thank Uppsala University for the patterned solar cells and the Danish Polymer Center at RISØ for the support in the projects.

References

Wind Energy with Power Plant Properties?

Jochen Möller
Ph.: +49 4856 901-14, Fax: +49 4856 901-49, e-mail: moe@windtest.de

Erik Tüxen
Ph.: +49 4856 901-24, Fax: +49 4856 901-49, e-mail: tx@windtest.de

About the Authors:

Jochen Möller joined the company WINDTEST 11 years ago as an electrical engineer. He is now head of the energy group and specialist in power quality measurement of wind turbines. Among other things he participates in the expert group of power quality by MEASNET and he is also coordinator for the German guidelines for the power quality measurements at wind turbines and for the German guideline for the measurement of the grid code requirements.

Erik Tüxen started at WINDTEST in February 2004 as a student apprentice. From July 2004 to February 2005 he wrote his diploma thesis about the improvement of the methods to determine flicker and harmonics caused by wind turbines. Additionally, he supported several power quality measurements as a student assistant. Since 21 February 2005, he works for the energy group as a power systems engineer. His main field of activity are power curve measurements.

Abstract

In the past wind turbines had to be disconnected from the grid as soon as possible on the occurrence of voltage disturbances. Because of the increasing development of wind energy the disconnection of wind turbines during voltage disturbances can in some regions cause a power loss of more than 3 GW. The European transmission operators can only provide 3 GW as short time power reserve for the UCTE grid. If the wind turbines cut off at a voltage drop, the European transmission operators will not be able to hold the voltage in the surrounding of the short circuit. Therefore wind turbines must try to support the voltage during a grid disturbance. After the transmission operators had presented these results to the wind turbine manufacturers, they made great efforts to optimise their products for these new requirements. Since 2003, WINDTEST measured the first prototypes, at first on test banks and later on wind turbines and wind farms. In addition to other measurements WINDTEST did more than 300 short-circuit tests in the medium voltage grid on a 2 MW wind turbine.

Our presentation shows the results and experiences of these measurements and would like to answer the question about the fault ride through capability of wind turbines. Additionally we show how the test can be done on the medium voltage side. We give some advice to the location of the measurement points for the current and voltage on the low and medium voltage level.
1 Introduction

Wind energy is no more hidden in a corner, depending on the wind rate it has a small or greater part of the German energy production. For more than ten years, the grid compatibility of wind turbines has been checked and continuously improved by the manufacturers. Compared to wind turbines 10 years ago, modern wind turbines today cause only 1/10 of the flicker.

As wind energy production increases, the grid operators (high and excess voltage grids) call for more requirements of the wind turbines. In front of all stands the E.ON Netz GmbH (E.ON grid, ENE). These demands are to be geared to the characteristics of conventional power plants and to the needs of feed-in certainties of the grid operators. Since the year 2000 problems of regulation of active and reactive power as well as the problem of supporting the grid in case of voltage drop have been discussed between grid operators, manufactures of wind turbines and measuring institutes. The meetings took place under the patronage of FGW (Fördergesellschaft Windenergie e.V.- Development Fund for Wind Energy). One result of these meetings are the grid connection regulations of ENE [2] and Vattenfall Europe Transmission GmbH (VET) [3], the grid connection guideline of the association of grid operators (VDN e.V.) [4] and a testing guideline FGW TR4 for grid connection properties [1]. WINDTEST Kaiser-Wilhelm-Koog GmbH (WTK) has attended the complete process of development of the grid connection regulations and the creation of TR4. WTK was the chairman at the creation of TR3 and TR4. During the last years, WTK has attended the development at the manufacturers of wind turbines by testing at the test bay, in the field, in wind farms and by creating guidelines. In that article, the experiences are to show how wind turbines can be used for the support of the grid.

2 Active power output

Demands to the power output can be reduced to three main points:

- Limiting of active power increase after voltage loss
- Reducing of active power according to setpoint setting
2.1 Active power increase after voltage drop

Because the grid has to restart operation in a controlled way, the increase of active power after voltage loss has to be limited. It is quite easy to realise the testing of this behaviour by cutting off and cutting in the voltage at the wind turbine.

\[ P_{WT_{60s}} \]

\[ \text{Max Gradient} \]

Figure 1: Restart after voltage loss

2.2 Variation of power according to setpoint setting

The grid operator wants to have the facility to reduce the fed-in power of the wind turbine to prevent a capacity overload of the transmission. That behaviour is demonstrated by tests at the wind turbine and at the wind farm, respectively. Figure 2 shows a test at a wind farm. The wind farm was operated with reduced power, according to setpoint setting, step width was 10 % of the grid connection power.

The maximum deviation to the setpoint setting and the maximum possible speed of active power regulations are measured.
3 Behaviour in case of grid disturbances

Up to now, wind turbines have immediately been cut off from the grid in case of grid disturbances. That made sense, as long as wind turbines did not have a noteworthy part of the energy production. By now, in some regions the part of wind generated energy is that big that a cut-off from the grid could not be regulated by the European grid operators. The wind turbines have to support the grid in case of voltage drop (e.g. caused by an electric arc at an open wire line). Otherwise it may come to area-wide cut-offs. Figure 3 shows the limiting curve for the voltage behaviour, above which the wind turbines are generally not to be cut off from the grid and are to support the grid. How to support the grid is not regulated in the grid connection regulations of ENE, VET and VDN.
In the last few years WTK was able to accomplish measurements at different concepts of wind turbines. These tests were made in co-operation with manufacturers, test plants and grid operators. Tests at test plants were made only to test the electrical drive section. The complete wind turbine has been tested at a field test. It has been checked it the wind turbine is able to identify a grid disturbance and to support voltage. The following specific values have been determined:

- The ability of the wind turbine to stay connected to the grid during the disturbance.
- The reactive current which can be fed in during a disturbance.
- The time that the wind turbine needs until it can feed in rated power, after problem elimination.

There have been tests with different voltage drops and different times. Beside of that, three-, two- and one-phase short-circuits have been measured. At the tests it was differed between partial load and full load.
4 Regulation of reactive power

ENE and VET as well as some foreign grid operators ask for a regulation of wind turbines and wind farms. Usually, the grid operator predetermines which reactive power is to be used. As well as in the regulation of active power, the manufacturers have acquired concepts to provide particular reactive power by the wind turbine or by additional phase shifters in the wind farm.

4.1 P(Q)-curve

In which range a wind turbine or a wind farm is able to regulate reactive power, depending on the active power, is determined by measuring the P(Q)-curve. As well the capacitive as the inductive range are being looked at. From that curve the range of reactive power can be extracted, which can be provided at a certain active power. Figure 5 shows this curve.
4.2 Regulation of reactive power by setpoint setting

Grid operators are to give the adequate reactive power through an interface. WTK measures the interface and documents all deviations to the allegations. By the modern converters, the wind turbines or the wind farms are able to adjust the reactive power very fast. Figure 6 shows a measurement in the generator reference arrow system in the level of 20 kV. The connected wind farm switches within one grid period from lagging to leading current.

Figure 6: Switching between the feed-in of inductive and capacitive power
Figure 7 shows a measurement at a transformer station. To this transformer station a wind farm is connected, which was driven through an interface. It was a part load measurement, started at a power factor of 0.95 inductive to 0.95 capacitive.

The minimum possible stepping is measured and specified.

**Generally, the allegations of the grid operators reference to the grid connection point.**

![cos_phi](attachment:cos_phi.png)

*Figure 7: Power factor according to setpoint setting in a wind farm*

### 5 Conclusion

Most of the well known manufacturers have optimised their wind turbines according to the demands of the grid operators. Some of the manufacturers have already got their wind turbines measured and certificated at the testing field. Most of them will start that in the coming months, to get assurance for future projects.

As explained in this article, some values are easy to measure, but some are more complex. Especially the short circuit tests need complex technique and the grid connection point has to be adequate to the short circuit tests. By measuring the wind turbines and the wind farms, the problems can be identified very early, so that they can generally be eliminated by the respective manufacturer.
6 References


[2] Netzanschlussregeln Hoch- und Höchstspannung; E.ON Netz GmbH, 01.08.2003


Session 14 – Technology Applications in Developing Countries

Chairman: Mark Radka, UNEP, Division of Technology, Industry and Economics, France
ETHANOL PRODUCTION FROM CORN, CORN STOVER AND CORNCOB FROM THE JILIN PROVINCE OF CHINA

Enikő Varga¹, Anne Belinda Thomsen¹, Ling Feng²

¹Risø National Laboratory, Biosystem Department, P.O. Box 49, DK-4000 Roskilde, Denmark
²Jilin Light Industry Design and Research Institute, 1358 Gongong Avenue, 130021 Changchun City, P.R.China

* Corresponding Author: Anne Belinda Thomsen
Phone: +45 4677 4164
Fax: +45 4677 4122
E-mail: anne.belinda.thomsen@risoe.dk

ABSTRACT

Among the available agricultural by-products, corn stover is far the most abundant lignocellulosic raw material for fuel ethanol production in China. More than 120 million tons of corn stover is produced annually, representing approximately 40 million tons of ethanol.

In this study ethanol was produced from corn and alkaline wet oxidized (WO) corn stover and corn cob followed by non-isothermal simultaneous saccharification and fermentation (SSF) using Saccharomyces cerevisiae. Eight different combinations of reaction temperature and time were applied for wet oxidation of corn stover and corn cob using Na₂CO₃ and NH₃ as catalysts to find the best reaction conditions, resulting in both high glucose and ethanol yield. The best condition (200°C, 8 min, 2g/L Na₂CO₃) increased the enzymatic conversion from cellulose to glucose of corn stover more than four times and resulted in 87% ethanol yield of theoretical, based on the cellulose available in the WO corn stover. This was achieved with a substrate concentration of 6% (w/w) dry material at 20 FPU/g DM enzyme loading after 120 h of SSF.

The pretreatment with NH₃ at the same conditions resulted slightly lower cellulose conversion to glucose, but also gave promising ethanol yield (75%), demonstrated, that the baker’s yeast still could adapt to the WO material and ferment the glucose content to ethanol efficiently.

Keywords: simultaneous saccharification and fermentation (SSF), wet oxidation, corn stover, corn, ethanol fermentation

1. INTRODUCTION

Global warming together with the continuously increasing energy demand are hot environmental issues. How do we reduce our use of fossil fuels, which add to the greenhouse effect? One alternative to the petrol used in motor vehicles is the clean burning fuel ethanol, which can be blended with gasoline up to maximum ethanol content of about 25 percent. Bioethanol offers a significant contribution to the future
challenge of a more sustainable fuel. In medium-term it makes possible the fulfilment of the Kyoto commitment that the European Union (EU) is determined to implement. To achieve this goal the EU has decided to raise the market share of biofuel in the transportation sector to 5.75% until 2010, but the further plan is to reach 20% by the end of year 2020i.

Bioethanol can be produced from a variety of biomass crops, but traditionally sugar- and starch–containing crops are used. Starch is relatively, easily converted to glucose by enzymes, after which glucose can be fermented to ethanol by conventional Baker's yeast. This starch-based technology is used in one of the world largest ethanol-producing factory in Jilin province of China, using corn as a substrate. China, following the USA, is the second biggest corn producer country in the World, harvesting more than 120 million tones of maize annually. This corresponds to 20% of the World’s total corn production.

In the year of 2000 the Chinese government decided to support the ethanol production for transportation fuel. A new bioethanol-producing factory was constructed in Jilin province, which is the biggest corn producing area in China, giving 15 percent of the entire Chinese corn production. This ethanol plant is capable of converting about 2 million tones of maize kernels to ethanol, but the fuel requirement is enormous – especially because the number of cars in China currently increases by 15-20 percent annually.

The relatively high cost of the corn and also the abundant amounts of corn stover (the straw from corn production, of which amount is approximately equal with the mass of corn), have generated a pressure to utilize corn stover as a feedstock for ethanol production, especially because of its high polysaccharide content (60-70%). Corn residue is a very important resource on a global scale, around 500 million tones of corn stover are produced annually worldwide, and that is a potential source of producing 140 million tons of bioethanol. Risø and Elsam Biosystems A/S have recently entered into a collaborative agreement with a number of institutions and companies in China's Jilin province. As a result of this agreement, collaboration will now be established regarding research, process development and production of ethanol from corn stover.

Due to structural features, such as presence of lignin, acetyl groups and cellulose crystallinity, corn stover and lignocellulosic biomass in general must be pre-treated to enhance its enzymatic digestibility before microbial conversion into liquid fuelsii. The wet oxidation processiii has been shown to be a promising pre-treatment method of herbaceous plants. For example, wet oxidation of wheat straw resulted in highly convertible polysaccharides, such as cellulose and hemicelluloseiv,v. This fractionation method breaks down the lignin structure and solubilizes the major part of hemicellulose fractionvi, thus enhancing enzymatic digestibility and the consequence fermentability of the raw materials. Our previous studies of corn stover showedvii, that the three most important wet oxidation parameters, which effects both the sugar and ethanol yieldsviii, are the concentration of the catalysts (usually Na2CO3), the temperature, and the residence time. During high temperature wet oxidation sugars and other degradation products can be formed from the xylan and the lignin fraction, such as acetic acid, formic acid and phenol monomersix,x, which might inhibit the fermenting microorganisms used in the downstream processing.

However according to our previous results on wheat straw and corn stover and corn cob, the concentration of these compounds were bellow the inhibitory level for the subsequent glucose fermentation by Saccharomyces cerevisiaeii, but was found to be inhibitory for the xylose fermentation by Thermoanaerobacter mathraniiix in concentrated WO
The aim of the present study was to apply wet oxidation to corn stover from Jilin province and investigate the influence of different pretreatment conditions on sugar yield and the effect of inhibitors on subsequent ethanol yield. For SSF experiments *S. cerevisiae* was chosen in the form of dried *baker’s yeast*, because *S. cerevisiae* is also used in the starch based alcohol factory in Jilin. In addition dried *baker’s yeast* has also the advantage of being quite robust and less sensitive to inhibitors formed by thermal pretreatment, than other cultivated yeast strainsxiii,xiv.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Corn plant was grown in Jilin province of China harvested in fall of 2004. The air-dried corn stover was ground to 3 mm particle size by using a knife mill. All materials were stored in the dark in paper bags at room temperature. The corn seeds were grind to an average particle size below 0.8 mm only directly before fermentation, the humidity of the seeds was approx. 15%.

### 2.2 Wet oxidation pre-treatment

Wet oxidation (WO) was carried out in a loop autoclave constructed at the Risø National Laboratoryxv. For optimization of corn stover a 2³-1 partial fractional design was applied using two different catalysts (Na₂CO₃ and NH₄OH) also to test their substitution capability. The pretreatment conditions are summarized in Table 1. 60g (DM) dry matter corn stover or corncob was mixed with 1 L water and 2 g Na₂CO₃ or 4 mL 25% (w/w) NH₄OH (corresponding to the concentration of 59 mM) before applying 12 bar oxygen pressure and heating the suspension. After the WO pre-treatment the slurry was separated into a liquid and a solid fraction, and both fractions were analyzed. Both the cellulosic solid fractions and the filtrates were stored frozen (-20ºC).

<table>
<thead>
<tr>
<th>No</th>
<th>Temperature</th>
<th>Time</th>
<th>Applied chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190</td>
<td>8</td>
<td>Na₂CO₃ / NH₄OH</td>
</tr>
<tr>
<td>2</td>
<td>190</td>
<td>16</td>
<td>Na₂CO₃ / NH₄OH</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>8</td>
<td>Na₂CO₃ / NH₄OH</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>16</td>
<td>Na₂CO₃ / NH₄OH</td>
</tr>
</tbody>
</table>

### 2.3 Analysis of raw material and WO cellulosic fractions

The composition of the dried raw material and the solid fibrous fraction remaining after pre-treatment were analyzed by strong acid hydrolysisxvi. Approx. 0.15 g DM solid material was weighed and hydrolyzed in 1.5 mL 72% H₂SO₄ for 1 hour at 30°C. Then 42 mL water was added and the capped Pyrex tubes were autoclaved 1 hour at 121°C. The acid hydrolyzate was filtered and the resulting monosaccharides (glucose, xylose and arabinose) were quantified by HPLC with refracting-index (RI) detection (Shimadzu Corp., Kyoto, Japan) after separation on an Aminex HPX-87H organic acid column (Bio-Rad Laboratories Inc., Hercules, CA, USA), using 4 mM H₂SO₄ as eluent with 0.6 mL/min flow at 63°C. Conversion factor for dehydration on polymerization to cellulose was 162/180 for glucose and to arabinoxylan was 132/150 for xylose and arabinose. The
residue was dried and weighed and reported as Klason lignin.

The ash content was determined by placing approximately 0.5 g sample in a tarred crucible that was ignited at 550°C for 3 hours, cooled in a desiccator, and weighed.

2.4 Analysis of the filtrates

The carbohydrates in WO filtrate, were quantified as monosaccharides gained after dilute sulfuric acid hydrolysis with 4% (w/w) H$_2$SO$_4$ at 121°C for 10 min. The sulphate anions in 10 mL acidic hydrolyzate were precipitated by 0.5 g Ba(OH)$_2$·8H$_2$O and the supernatant was diluted 1:1 with 4 mM H$_2$SO$_4$. Average recovery for glucose, xylose and arabinose was 86, 83 and 86%, respectively. Glucose, xylose and arabinose were quantified by HPLC as previously described. Monosaccharides (xylose, arabinose, glucose) were quantified with the before mentioned HPLC conditions by RI-detection using an Aminex HPX-87H column at 63°C. The mobile phase was 4 mM H$_2$SO$_4$ at a flow rate of 0.6 mL / min.

2.5 Simultaneous saccharification and fermentation (SSF) on pretreated corn stover

SSF experiments were performed in 0.25 L blue cap flasks filled with 100 g substrate under semi-sterile conditions. The flasks were fitted with yeast locks constructed to let CO$_2$ pass through a glycerin trap. The wet oxidized, washed material was diluted with the separated liquid fraction resulting in final substrate concentration of 6% (w/w) DM. The pH was adjusted with 1 M NaOH or with 1 M H$_2$SO$_4$ to pH 4.8. The flasks were sterilized by heat in autoclave, but neither the solid, nor the liquid fraction derived from WO of corn stover were sterilized to avoid further high temperature decomposition of the wet oxidized material. The enzyme solutions were not sterilized either.

In the first step of SSF the pre-treated corn stover was pre-hydrolyzed at 50°C for 24 hours with enzyme loading of 15 FPU/g DM. Following pre-hydrolysis cellulase was added again, using enzyme loading of 20 FPU/g DM, simultaneously with dried Baker’s yeast (1 g/L) and urea (2 g/L) as a nitrogen source. Both in the pre-hydrolysis and in the SSF step β-glucosidase was added as a supplement at ratio of 1:1 IU of β-glucosidase to IU cellulase. It was shown in previous studies that the β-glucosidase supplementation is necessary to achieve efficient cellulose conversion, however the used cellulase mixture in Celluclast 1.5L contains some β-glucosidase activity. Commercially available cellulase from Trichoderma reesei (Celluclast 1.5L) and β-glucosidase (Novozym 188), were applied in the pre-hydrolysis and also in the SSF step. Both enzyme preparations were kindly delivered by Novozymes A/S (Bagsværd, Denmark). The glucose concentration in both enzyme solutions was determined by HPLC, and was found less, than 1.3 ppm (mg/L).

The fermentation was carried out in duplicates at 30°C for 120 h and the flasks were agitated at 150 rpm. After the SSF the samples were cooled on ice immediately and centrifuged at 4000 rpm for 10 minutes. Ethanol concentration and the remaining monosaccharides were determined by HPLC at the previously described conditions.

Weighing the flasks at regular intervals to follow CO$_2$ loss monitored the fermentation rate. In this case the ethanol yield was calculated from the CO$_2$ loss by multiplication of the conversion factor 1.045 (e.g. the molar ratio of EtOH/CO$_2$). The formula for calculating the weight of produced ethanol from CO$_2$ losses the following Equation 1.

\[
\text{EtOH (g)} = \text{CO}_2 \text{ loss (g)} \cdot 1.045
\]

Equation 1
The final ethanol concentration was also measured by HPLC. The ethanol yield was calculated assuming that 1 g of glucose present in the liquid theoretically gives 0.51 g of ethanol and 1 g of cellulose gives 1.11 g of glucose. This yield is always less than 100%, as a part of the sugars is needed for cell growth and synthesis of other by-products, such as glycerol and lactic acid.

2.6 Liquefaction, saccharification and fermentation of corn

Liquefaction and saccharification of corn was performed in a 1 L blue cap flasks filled with 900 g sterilized tap water blended with 15% (DM) ground corn and add 0.1 µL/g DM Liqozym SCN for liquefaction. The flask was put in a water bath at 60°C for 45 min and stirred intensively (300 min⁻¹), following the temperature was increased to 90°C and stirred further. After 45 min the temperature was lowered to 60°C and the hydrolysis was continued with saccharification enzyme (0.3µL/g DM Spirizym) for 15 min. Both enzyme preparations were kindly delivered by Novosymes A/S (Bagsvaerd, Denmark). The liquefied hydrolyzate was cooled and supplemented with nutrients to a final concentration of 0.5 g/L sterile filtered urea, 0.1 g/L (NH₄)₂HPO₄ and 0.3 g/L yeast extract. Then the hydrolyzate was transferred to the 2.5 L glass fermenter (Miniforse, Appropriate Technical Resources, Inc., Laurel, MD, US). It was inoculated with *S. cerevisiae* suspend in 10 mL sterile water, getting an initial yeast DM concentration of 0.5g/L. In the first 10 hours of starch fermentation continuous airflow was applied together with intensive stirring (200 min⁻¹) to stimulate yeast growing, then the air was stopped and the stirring was moderated to 50 min⁻¹. The pH (4.2), the temperature (32.5°C) and the stirring (50 min⁻¹) were controlled and kept constant during the fermentation.

The fermentation was carried out in duplicates for 72 hours and was sampled in every 12 hours. The samples were cooled on ice immediately and centrifuged at 4000 rpm for 10 minutes. Ethanol concentration and the remaining glucose were determined by HPLC.

2.7 Enzyme activity measurement

The activity of the cellulytic enzymes was measured in filter paper units (FPU). A 1 x 6 cm strip of a Whatman No. 1 filter paper was added to 1.5 mL enzyme solution containing 0.05 M Na-citrate buffer, pH 4.8. The samples were incubated 1 hour at 50°C. Reducing sugars were determined after stopping the hydrolysis by addition of 3 mL dinitro-salicylic acid solution followed by 5 minutes boiling. After cooling, 20.0 mL distilled water was added and the UV-absorbance was read at 540 nm.

The ß-glycosidase activity was measured by incubating the enzyme solution with 10 M p-nitrophenyl-ß-D-glucopyranoside and 0.05 M citrate buffer, pH 4.5 at 50°C for 10 minutes. The reaction was stopped by addition of 0.1 M Na₂CO₃ and the amount of liberated p-nitrophenol measured spectrophotometrically at 400 nm. One unit of activity (IU) was defined as the release of 1 µmol of p-nitrophenol per minute.

3. RESULTS AND DISCUSSION

3.1 Fermentation substrate by wet oxidation pre-treatment of corn stover

Wet oxidation of Hungarian corn stover at alkaline pH, at 195°C for 15 minutes with 12 bar oxygen was previously found to be very efficient for increasing the cellulose
convertibility to glucose, and has the advantage of high sugar recoveries\textsuperscript{viii}. However the behavior of the raw material during WO slightly differs from year to year, and this difference could be bigger, when the material originated from different filed or even from different country with different climate, like in this case. That was why it was necessary to make a quasi optimization of pretreatment on Chinese corn stover as well.

The chemical composition of the wet oxidized solid fibrous fractions varied considerably with the reaction conditions. Compared to the original corn stover alkaline pre-treatments both with Na\textsubscript{2}CO\textsubscript{3} or NH\textsubscript{3} catalysts resulted in solid fraction enriched in cellulose and diminished in hemicellulose. Compositions of native corn stover and corncob and also the pre-treated solid fibrous fraction determined by strong acid hydrolysis is shown in Table 2. The amount of hemicellulose in the solid residue was calculated from the amount of xylene and arabinose and cellulose was calculated from the amount of glucose in the supernatant following strong acid hydrolysis. The amount of extracted sugars in g/kg corn stover derived from WO is summarised in Table 3.

Table 2. Composition of solid fraction after WO (g/100 g untreated raw material)

<table>
<thead>
<tr>
<th>Corn stover</th>
<th>Wet oxidation conditions</th>
<th>Solid fraction (g/100 g original DM)</th>
<th>Temp. (°C)</th>
<th>Time (min)</th>
<th>Chemicals</th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>8</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>29.1</td>
<td>12.9</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>26.8</td>
<td>6.4</td>
<td>8.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>25.1</td>
<td>5.7</td>
<td>10.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>24.3</td>
<td>2.3</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>8</td>
<td>NH\textsubscript{3}</td>
<td>28.9</td>
<td>6.5</td>
<td>13.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>NH\textsubscript{3}</td>
<td>24.8</td>
<td>3.7</td>
<td>8.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>NH\textsubscript{3}</td>
<td>27.8</td>
<td>2.5</td>
<td>13.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>NH\textsubscript{3}</td>
<td>24.8</td>
<td>2.0</td>
<td>12.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untreated corn stover</td>
<td></td>
<td></td>
<td>35.9</td>
<td>25.1</td>
<td>19.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Corncob</th>
<th>Wet oxidation conditions</th>
<th>Solid fraction (g/100 g original DM)</th>
<th>Temp. (°C)</th>
<th>Time (min)</th>
<th>Chemicals</th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>8</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>24.6</td>
<td>11.8</td>
<td>9.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>24.1</td>
<td>4.1</td>
<td>8.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>26.7</td>
<td>6.7</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>Na\textsubscript{2}CO\textsubscript{3}</td>
<td>23.2</td>
<td>4.1</td>
<td>7.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>8</td>
<td>NH\textsubscript{3}</td>
<td>24.2</td>
<td>10.0</td>
<td>12.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>NH\textsubscript{3}</td>
<td>24.5</td>
<td>3.6</td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>NH\textsubscript{3}</td>
<td>22.2</td>
<td>4.2</td>
<td>11.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>NH\textsubscript{3}</td>
<td>21.2</td>
<td>3.4</td>
<td>13.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untreated corncob</td>
<td></td>
<td></td>
<td>31.40</td>
<td>29.9</td>
<td>22.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WO attacked mainly the hemicellulose fraction, and the harsher the pre-treatment conditions were the higher amount of hemicellulose disappeared from the solid fraction. Under the harshest condition (200°C, 16 min, 12 bar oxygen) almost all hemicellulose was removed from the solid fraction, this decreased from 25.1 g in the native corn stover to 2.3 g and 2.0 g using Na\textsubscript{2}CO\textsubscript{3} and NH\textsubscript{3} respectively. However, more than 50% of the original hemicellulose content was removed even at the mildest conditions (190°C, 8
To compare the two different catalysts during WO, ammonia seems to be slightly more effective in extraction of hemicellulose than Na₂CO₃, but Na₂CO₃ was more effective in delignification during the same reaction conditions. Approximately 50% of the initial lignin content was solubilisation and/or degradation of the lignin during all pretreatment.

The recovery both of hemicellulose and cellulose sugars is an important point of a suitable pre-treatment. The recovery of cellulose and hemicellulose was calculated to estimate their losses during WO pre-treatment at different conditions (Table 3.). The calculation according to the Equation 2 and 3 was based on the mass balance (Table 2-3).

**Table 3.** Composition of liquid fraction after WO (g/100 g untreated raw material), and recovery of polysaccharides (%)

<table>
<thead>
<tr>
<th>Wet oxidation conditions</th>
<th>Liquid fraction (g/100 g original DM)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn stover</td>
<td></td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>Time (min)</td>
<td>Chemicals</td>
</tr>
<tr>
<td>190 8</td>
<td>Na₂CO₃</td>
<td>1.9</td>
</tr>
<tr>
<td>190 16</td>
<td>Na₂CO₃</td>
<td>2.1</td>
</tr>
<tr>
<td>200 8</td>
<td>Na₂CO₃</td>
<td>1.8</td>
</tr>
<tr>
<td>200 16</td>
<td>Na₂CO₃</td>
<td>1.8</td>
</tr>
<tr>
<td>190 8</td>
<td>NH₃</td>
<td>2.2</td>
</tr>
<tr>
<td>190 16</td>
<td>NH₃</td>
<td>1.4</td>
</tr>
<tr>
<td>200 8</td>
<td>NH₃</td>
<td>2.2</td>
</tr>
<tr>
<td>200 16</td>
<td>NH₃</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Corncob</td>
<td></td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>Time (min)</td>
<td>Chemicals</td>
</tr>
<tr>
<td>190 8</td>
<td>Na₂CO₃</td>
<td>1.8</td>
</tr>
<tr>
<td>190 16</td>
<td>Na₂CO₃</td>
<td>1.5</td>
</tr>
<tr>
<td>200 8</td>
<td>Na₂CO₃</td>
<td>1.0</td>
</tr>
<tr>
<td>200 16</td>
<td>Na₂CO₃</td>
<td>1.3</td>
</tr>
<tr>
<td>190 8</td>
<td>NH₃</td>
<td>1.4</td>
</tr>
<tr>
<td>190 16</td>
<td>NH₃</td>
<td>1.3</td>
</tr>
<tr>
<td>200 8</td>
<td>NH₃</td>
<td>1.7</td>
</tr>
<tr>
<td>200 16</td>
<td>NH₃</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Recovery Cellulose (%) = \[\frac{\text{Cellulose in solid residue} (\text{g}) + \frac{\text{released glucose in filtrate} (\text{g})}{1.11}}{\text{cellulose in raw material} (\text{g DM})}\]

Equation 2

Recovery Hemi-cellulose (%) = \[\frac{\text{Hemi-cellulose in solid residue} (\text{g}) + \frac{\text{released xylene in filtrate} (\text{g})}{1.136}}{\text{hemi-cellulose in raw material} (\text{g DM})}\]

Equation 3

Table 3 shows, that hemicellulose extraction was more significant during WO, than cellulose solubilisation at all tested conditions. At 190°C, increasing the reaction time resulted in higher hemicellulose solubilisation was observed with both catalysts. At
200°C, longer pretreatment time has stimulated the hemicellulose solubilisation using 
Na₂CO₃, but using NH₃ as a catalyst it had a clear negative effect on it. In general, 50% 
of the original hemicellulose recovered, except when 200°C was combined with high 
reaction time and 59 mM NH₃. In this case, the hemicellulose recovery was only 38% 
due to hemicellulose degradation to other non-detected by-products, however milder 
reaction conditions resulted in higher recoveries. The cellulose recoveries were much 
higher, varied between 71.7-86.8%. The maximal recovery of both polysaccharide (74% 
of hemicellulose and 86.8% of cellulose) was obtained following the pre-treatment at 
190°C for 8 minutes using 2g/L Na₂CO₃.

The overall recovery of all sugars varied from 65% to 81.6% at 190°C and from 58% to 
69.9% at 200°C, which was a bit lower than achieved with Hungarian corn stover using 
wet oxidation. This indicates, that further optimisation on the Chinese corn stover is 
needed to obtain higher recoveries.

### 3.2 Enzymatic hydrolysis

The pre-treated solid residue was enzymatically hydrolysed to determine the degree of 
cellulose conversion to glucose (ECC%), which is valuable information to the 
effectiveness of the pre-treatment. The achieved conversion after 24 h enzymatic 
hydrolysis is shown in Table 4. The enzymatic conversion of pre-treated cellulose was 
between 63 and 78.5% compared to 16.4% obtained at enzymatic hydrolysis of the 
untreated corn stover. The ECC conversions in general were slightly higher following 
pre-treatment using Na₂CO₃ compared to NH₃. The highest conversion (78.5%) was 
achieved with a pre-treatment at 200°C for 8 minutes with 2g/L Na₂CO₃. However the 
highest amount of total released glucose (21.4 g glucose /100 g untreated corn stover 
DM corresponding to 60% glucose yield) was obtained after WO at 190°C for 8 minutes 
also with 2g/L Na₂CO₃. It could be explained with the higher amount of WO extracted 
glucose.

### 3.3 Ethanol yields on corn and on WO corn stover

Table 4 shows the achieved ethanol concentrations determined by HPLC, after 120 hours 
fermentation and the calculated ethanol yield. After 5-days fermentation the ethanol 
concentrations varied from 9.4 to 14.5 g/L corresponding to 59.3 and 87.4% of the 
thoretical ethanol yield. SSF of alkaline wet oxidized corn stover (200°C, 8 min 2 g/L 
Na₂CO₃) resulted in the highest ethanol concentration of 14.5 g/L, corresponding to 
87.4% of the theoretical. However, the ethanol yields were above 60% after all SSF 
followed different WO conditions. The lowest ethanol concentration and also the lowest 
ethanol yield were obtained, when the lowest temperature was combined with the 
shortest reaction time during WO and it was independent on the applied catalyst.

For the ethanol fermentation on corn an industrial scale optimized procedure was used 
(optimized by the ethanol producing factory in Jilin) in our laboratory scale equipment. 
The achieved ethanol concentration varied between 37.7-39.7 g/L, corresponding to 76- 
80% of the theoretical yield. This ethanol yield is slightly lower, than it used to be in 
industrial scale fermentation, but it could be explained with the non-optimized conditions 
in downscale. The highest ethanol concentration (39.7%) was achieved when the corn 
grain was fermented. This concentration was nearly two times higher, than using WO 
corn stover, but in this case only the cellulose content was fermented, which only 38% of 
the dry matter, while the starch content in the maize is 72%. However the hemicellulose 
fraction also could be used as a carbon source for ethanol fermentation.
Table 4. Ethanol concentration and yield after 120 h SSF on WO corn stover and 72 h fermentation on corn

<table>
<thead>
<tr>
<th>Wet oxidation conditions</th>
<th>ECC (%)</th>
<th>Total Glucose Yield (%)</th>
<th>Ethanol conc. (g/L)</th>
<th>Ethanol Yield (% of theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temp. (°C)</strong></td>
<td><strong>Time (min)</strong></td>
<td><strong>Chemicals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>8</td>
<td>Na₂CO₃</td>
<td>65.8</td>
<td>59.8</td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>Na₂CO₃</td>
<td>69.7</td>
<td>56.0</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>Na₂CO₃</td>
<td>78.5</td>
<td>58.6</td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>Na₂CO₃</td>
<td>69.4</td>
<td>52.1</td>
</tr>
<tr>
<td>190</td>
<td>8</td>
<td>NH₃</td>
<td>63.4</td>
<td>57.2</td>
</tr>
<tr>
<td>190</td>
<td>16</td>
<td>NH₃</td>
<td>77.2</td>
<td>57.2</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>NH₃</td>
<td>63.5</td>
<td>55.3</td>
</tr>
<tr>
<td>200</td>
<td>16</td>
<td>NH₃</td>
<td>68.3</td>
<td>49.8</td>
</tr>
<tr>
<td>Untreated corn stover</td>
<td></td>
<td></td>
<td>16.4</td>
<td>16.4</td>
</tr>
<tr>
<td>Corncob</td>
<td></td>
<td></td>
<td>8.7</td>
<td>66.1</td>
</tr>
<tr>
<td>Corn</td>
<td></td>
<td></td>
<td>59.5</td>
<td>80.0</td>
</tr>
</tbody>
</table>

### 4. CONCLUSION

This study shows that wet oxidation is an efficient method to increase the enzymatic accessibility of the water-insoluble, cellulose-rich component in corn stover and produce easily fermentable sugars to ethanol. After pre-treatment, the enzymatic conversion from cellulose to glucose increased nearly four times, compared to the untreated corn stover. The best pre-treatment conditions for obtaining high conversion of cellulose to glucose was 200°C for 8 minutes using 2 g/L Na₂CO₃ as a catalyst. Most of the hemicellulose was dissolved during the pre-treatment and approximately 50% of the original hemicellulose and in average more, than 80% of cellulose could be recovered. The enzymatic hydrolysis at 50°C was completed after 24 hours and the highest enzymatic conversion from cellulose to glucose was above 75%.

The fermentability of the pretreated corn stover gave promising results. The highest ethanol concentration 14.5 g/L, corresponding to 87.4% of the theoretical was achieved after WO carried out at 200°C for 8 min with 2 g/L Na₂CO₃ catalyst. However the ethanol yield was above 60% in all cases, which indicates that baker’s yeast could adapt to the pre-treated liquor and ferment the released glucose to ethanol. Based on our best results achieved by our laboratory scale experiments from for production of 1 L ethanol approx. 1.5 kg corn grain or 3 kg corn stover is necessary converting only its cellulose content. However utilising also the hemicellulose content in the corn stover the required amount could be decrease by approx. 30%.

The Danish know-how in lignocellulose pretreatment could be used in the design and dimensioning of a pilot plant to be constructed in Jilin. The production of bioethanol in Jilin will help reduce the discharge of greenhouse gases, and Denmark can benefit from that. According to the Kyoto Protocol, Denmark can include the amount of CO₂ reduction that results from Danish investment in China in the Danish greenhouse gas accounts.
ACKNOWLEDGEMENT
This research was supported by the Risø National Laboratory and by Jilin Light Industry Design and Research Institute.

REFERENCES

Session 15 – Energy Markets

Chairman: Hatem Marzouk, European Institute for Energy Research, Germany
Investments in Liberalised Power Markets

Stine Grenaa Jensen¹ and Peter Meibom²

¹Corresponding author, Risø National Laboratory, Frederiksborgvej 399, DK-4000 Roskilde, tel. 4677 5113, Fax: 4677 5199, e-mail: stine.grenaa@risoe.dk
²Risø National Laboratory, Denmark

Abstract

There is considerable uncertainty in the Nordic electricity system with respect to the long-term development in production capacity. The process towards liberalisation of the electricity sector started with a situation of a large capacity margin, but this margin is gradually vanishing. Since the potential investors in new production capacity are unaccustomed with investments under the new regime, it is unknown if and when investments will take place.

The purpose of the present study is to analyze if and when investors choose to invest in new electricity production capacity depending on their existing portfolio of power producing units. Electricity price scenarios generated with a partial equilibrium model (Balmorel) are combined with a model of investment decisions. In this, various scenarios concerning the development in the Nordic power market, such as new transmission lines between neighbouring countries, more installed wind power, and changes in CO₂ emission trading costs, are used to investigate the consequences for investments in a natural gas fired, combined cycle power plant.

The main result of the analysis is that new investments are highly sensitive to investors existing power production portfolio, as new production units affect the merit order in the power market, i.e. compete with the existing power plants.

Keywords: investment, power market, portfolio, and equilibrium models

1 Introduction

A key priority in the European Union is to ensure security of electricity supply (EC, 2004), which among other things depend on the timing and amount of new investments in power plants. There are no mandatory expansion plans within a liberalised electricity market that determine the type, timing and amount of new generation units in order to ensure security of supply. Instead, market participants decide from a business expectation perspective. Several studies in economic theory (e.g., Hirst, 2003) indicate that the spot market itself is capable of providing adequate investment signals in order to generate new investments when needed. Yet, there are several obstacles for these investments.

The present study analyses the possibility of new investments considering the fact that current market actors are most likely to reinvest, and hence invest under consideration of a whole portfolio, and not only by considering the new investment alone. The emphasis is on two points. One is the establishment of a numerical model that through simulation can provide estimates of price signals (electricity spot prices) for future years with sufficient (hourly) time resolution. For this purpose, the Balmorol model has been extensively updated with respect to data for the Nordic countries, and a scenario for the
future development of the Nordic power system has been constructed (for example, with respect to development in the electricity and heat demand, fuel prices, development of electricity demand elasticity).

The other point is the establishment of a numerical model that provides optimal investor response to price signals, based on modern investment theory, viz., real-options theory and decision-trees. The combination of the two models allows simulation of investment decisions that are taken in a stochastic, dynamic setting, where a key point is the timing of the investment decisions in relation to the gathering of new information relative to the stochastic elements.

The structure of the paper is as follows. The first section introduces the model framework including a brief introduction to the used simulation model, and to the investment theory used to conduct the analyses. Next the results are presented from two perspectives, one with emphasis on the role of how investors behave on a liberalized power market in case of no other positions at the power market, and one with emphasis on the investor holding a portfolio of operating power plants.

2 Model

In this section, the model framework will be explained. We have chosen to use a model framework that relies on an exogenous investment module that interacts with an underlying partial equilibrium model of the Nordic electricity market feeding the investment module with input in form of cash-flow values. These cash-flow values are then discounted with an adjusted discount rate. The producers are assumed to be price takers, i.e., no market power will be exercised.

The investment module uses a representation in the form of decision-trees. A decision-tree is constructed by ordering possible investment decisions and outcome of events in a sequential, tree-like fashion showing explicitly the time dependencies between event outcomes and investment decisions. The partial equilibrium model of the Nordic electricity market, Balmorel, is used to deliver input data to the decision tree in the form of prices and costs linked to each node in the decision-tree, i.e., each combination of investment possibility and event outcome.

This interaction between models has been chosen in order to obtain consistency between investment decisions and market prices. The consistency problem arises as new investments and event outcomes influence the spot prices in the market, and the spot prices in turn influence the investment decisions. This dynamic is not captured, if we use an investment model with input prices formulated as a stochastic process that are independent of the realized investment decision as is common in many studies using the real option methodology (e.g., Deng, Johnson and Sogomonian 2001).

Furthermore by translating uncertain, future developments in the power market into a sequence of events in the decision tree, this approach allows option values of holding an investment opportunity to be calculated as a function of these uncertain events. Thereby the influence of e.g. the future development of CO₂-markets or the future deployment of renewables on the investment decisions to be considered today can be analyzed. The interaction of the different modules is illustrated in Figure 1.
2.1 Balmorel

The Balmorel model is a partial equilibrium model covering the electricity and combined heat and power (CHP) sectors in the four Nordic countries Denmark, Finland, Norway and Sweden (Ravn & al. 2001). The model is linear, and assumes perfect competition.

Data in the applied model combine historical data (for electricity and heat demand, wind power production and others) with scenarios for the future development in heat and power demand and installed capacity. In the present version, one week at a time is simulated and the time unit used is one hour.

In Norway and Sweden, most electricity is produced from hydropower and as the production of hydropower is strongly dependent on long-term aspects, it is necessary when simulating a week to introduce boundary conditions. This is done by specifying a boundary condition where the total production level from hydropower for each week and each region is specified based on input from a long-term version of Balmorel optimising the use of hydro power over a yearly horizon.

The exchange between the countries modelled is determined endogenously, according to relative prices and transmission capacities. The exchange between the modelled (Nordic) countries and Germany/Poland is represented using a price interface calibrated with the use of the long-term version of Balmorel to ensure a yearly, zero net import between the Nordic system and the continent. The exchange between Finland and Russia is specified with fixed values giving a net yearly, import to Finland from Russia of 11 TWh.

Capacity and technology data for the units in the present power system are taken from the data set by Elkraft described in Elkraft (2003). These data have been supplemented with a few other units to secure the best possible correspondence with aggregated capacity data distributed on main technology and fuel types published by Nordel (www.nordel.org).

One scenario for the development of the installed capacity in the period 2005-2022 has
been constructed. In the whole period, 1% per year of the installed capacity of thermal power plants except nuclear power plants is decommissioned. With regard to investments, the scenario constructed is a low investment scenario. We have used the investments in the period 2005-2010 that are already planned today, and that according to our judgment are likely to be realised. In the period 2011-2022, no investment takes place.

The total installed capacity including wind power is relatively constant throughout the period as seen from Figure 3.

![Development in available capacity exclusive reserve capacity but including the installed capacity of wind power compared to peak load demand in a normal winter in the Nordic power market system.](image)

Figure 2: Development in available capacity exclusive reserve capacity but including the installed capacity of wind power compared to peak load demand in a normal winter in the Nordic power market system.

The development in the yearly power consumption in the period 2004-2022 is based on (Nordel, 2002). The increase in peak demand including distribution losses during the period 2004-2020 is approximately 9000 MW, which combined with the constant installed capacity during the period results in a progressively tighter capacity balance during the period.

2.2 Investment Module

An investment decision in power producing capacity consists of a lot of choices involving type, size, timing, placement, etc. These decisions are linked together by a rent ability evaluation of different investment combinations. The most used method for evaluation is the net present value calculation including value of future contribution margins, risk adjustment, and managerial flexibility. The different methods for investment evaluation can be distinguished in the way risk and flexibility are treated, along with the assumptions of investors’ preferences to these two subjects (Lemming & Meibom, 2003).

Decision-trees expand on the traditional net present value approach by allowing the investor to take action as time goes by and more information is obtained. The optimal decision for the investor is found by backwards induction of the decision-tree, whereby optimal strategies will be dependent on uncertainty in the different events. These uncertain values are realised in the decision-tree as events are revealed. Each cash-flow value is adjusted with an adjusted discount rate, in order to express other uncertainties in
the decision analysis. The estimation of such a discount rate is very difficult, so, in this case, we chose to perform sensitivity analysis on this parameter later in the paper.

In order to describe events along the selected time horizon (2006-2022), we have chosen to divide them into two groups. Firstly, a group with changes related to the investors’ decisions (timing, type, placement, size, etc.). Secondly, a group with changes related to events happening independent of the investors’ actions, i.e., changes in the system surrounding the investment decision (other investments, changes in transmission capacity, changes in demand, legal setup, etc.).

**Investment Possibilities**

To avoid creating a very large decision tree, we choose to focus only on the following:

- **Timing**: One of the option values is timing of the investment. In this case, there is a possibility to invest in four different points in time (2006, 2009, 2011, and 2013), following which the investor only has a possibility to postpone the investment for 7 years. After this, the investment possibility no longer exists.

The type of investment, we investigate in this paper is a combined heat and power gas turbine (combined cycle) (CCNG) with 500 MW power capacity situated in East Denmark (Eltra, Elkraft, and Danish Energy Authority, 2004, page 29).

![Figure 3: Overview of the investor’s options. This tree is used to evaluate a combined cycle gas turbine.](image)

Furthermore, we include two different views on the investor. One, considering an investor that do not hold any other power plants in this market, wherefore the profitability of the investment is made only by comparing annualised investments costs, variable costs, fixed costs and income. The other case is the case where the investor does hold other power plant investments, such that the profitability also depends on the effect the new investment has on power prices in the market, and hence the decrease in income of the rest of the portfolio.

This effect for the rest of the portfolio can be illustrated in Figure 4, where the same quantity ($\Delta q$) that are added to the supply curve with lower marginal costs than the
current market price ($p_1$ or $p_2$) can have a very different impact on the price determination. Following, adding the quantity $\Delta q$ can have a small impact on prices if the power price is low ($p_1$), while the effect grows with higher prices ($p_2$), where the capacity balance is much tighter. This effect leads to a negative correlation between capacity balance and profitability of new investments for existing market players.

\[ \Delta p_1 \quad \Delta p_2 \quad \Delta q \]

Figure 4: Illustration of the effect from increase in capacity with high and low power prices, where $\Delta q$ is the quantity being added to the system, and $\Delta p_1$ and $\Delta p_2$ are the following price changes.

Following, the analyses on profitability will be conducted in two cases:

- Investor holding no other investments at the power market
- Investor holding a portfolio of investments at the power market

The analysis only considers the behaviour of one investor, which corresponds to assuming the existence of market barriers on the power market, shielding our investor from competing investors.

Events

In these analyses, we have chosen to put particular interest in political decisions, which over time can have large impact on option values in an investment. These three events are:

- Development of the transmission system
- Development of wind power
- Development in emission permit markets for CO$_2$

Development of the Danish transmission system represents the situation, where transmission capacity are extended on Skagerak between Denmark and Norway with 600 MW and Storebælt connecting Eastern and Western Denmark likewise with 600 MW (Nordel, 2004). The connections are established in 2008, if the outcome is building the connections, and the alternative is not to build them at all. The outcome of the event is known in 2008, hence no lead time is included in the analyses.

Development of wind power covers the case, where Danish wind power production reaches a level at 35 % of consumption in the year 2015. This event is modelled in such
a way that the decision about the future level of wind power is known in 2010, following a building of offshore wind farms with 822 MW in total in both east and west in the period 2011 – 2015. The opposite outcome is no extra wind power capacity.

Development in emission permits markets for CO2 is included in order to illustrate the situation where Europe has a price at 50 DKK/ton CO2 in the period 2005 - 2012. Hereafter, the price can either stay at 50 or increase to 150 depending on the participation of the United States in the permit market after the first Kyoto period. The outcome of this event is known in 2012.

<table>
<thead>
<tr>
<th>Event</th>
<th>Decision</th>
<th>Outcome 1</th>
<th>Outcome 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>2008</td>
<td>No change</td>
<td>Skagerak (600 MW) and Storebælt (600 MW).</td>
</tr>
<tr>
<td>Wind Power</td>
<td>2010</td>
<td>No change</td>
<td>Development with app. 800 MW totally in both Eastern and Western Denmark in the period 2011-2015.</td>
</tr>
<tr>
<td>CO2 Price Level</td>
<td>2012</td>
<td>50 DKK/ton</td>
<td>150 DKK/ton</td>
</tr>
</tbody>
</table>

*Table 1: Events in used in the analyses.*

*Figure 5: Event tree*

These three events can be listed in an event tree, which in combination with the investment-tree can form a decision-tree that represents the different scenarios that arises from combination of events and investments.
3 Results

Balmorel calculations with the baseline investment scenario give price series with a very strong increasing trend in prices, especially after 2010 (Figure 7). This trend is based on the assumptions made in the baseline, where no investments are introduced after 2010. Therefore, this scenario is a worst-case scenario, but nevertheless it is useful to illustrate, how high the price level has to be in order to generate new investments in the Nordic power market.

![Figure 7: Price Series with Baseline Investment Scenario](image)

**Figure 7: Price Series with Baseline Investment Scenario**

3.1 Investor Holding No Other Investments at the Power Market

In the first case, the analyses show that the net income per year cannot cover the annualised investment costs every year in the period (2006-2010) (Figure 6). Therefore, an investor, who does not hold other investments at the power market, would delay the investment until 2010, using an assumption of a discount rate at 10% and equal probabilities for each outcome of the events.

![Figure 6: Weekly average prices for Eastern Denmark 2004 to 2022.](image)

**Figure 6: Weekly average prices for Eastern Denmark 2004 to 2022.**
Following, the option value is positive, since it is now possible to avoid unprofitable years during the investment horizon. This is illustrated in Figure 7, where investment in 2010 gives a possibility to avoid the unprofitable years 2006, 2008, and 2009. The reason for investor not to avoid 2010 and 2011 is that the revenue in 2012 compensates for these two unprofitable years, and since there is no possibility to invest in 2012 he chooses 2010.

The result is very sensitive towards the selected discount rate, which is illustrated in the sensitivity analysis in Table 2.

<table>
<thead>
<tr>
<th>Discount Rate</th>
<th>Investment Value</th>
<th>Option Value</th>
<th>Optimal Investment Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0%</td>
<td>1597</td>
<td>0</td>
<td>2006</td>
</tr>
<tr>
<td>2.5%</td>
<td>1103</td>
<td>0</td>
<td>2006</td>
</tr>
<tr>
<td>5.0%</td>
<td>743</td>
<td>0</td>
<td>2006</td>
</tr>
<tr>
<td>7.5%</td>
<td>484</td>
<td>5</td>
<td>2008</td>
</tr>
<tr>
<td>10.0%</td>
<td>306</td>
<td>24</td>
<td>2010</td>
</tr>
<tr>
<td>12.5%</td>
<td>200</td>
<td>66</td>
<td>2013</td>
</tr>
<tr>
<td>15.0%</td>
<td>130</td>
<td>108</td>
<td>2013</td>
</tr>
</tbody>
</table>

Table 2: Optimal investment decision depending on discount rate (risk premium) (all event probabilities are at 50%). Notice that a positive option value leads to a delay in the investment decision.

Figure 8: NPV for combined cycle when investing in 2010 for each of the eight event combinations shown in Figure 5.

Figure 8 can be used to describe the different effects on NPV of the eight combinations of the chosen events. The first column from the left is the situation with the base case. Development of the transmission capacity has a smaller positive effect for the investment. Extra wind power capacity opposite has at negative effect, and finally, an increasing CO₂ price level has a positive contribution to the total revenue for the
The positive correlation between CO₂ price and revenue is caused by the marginal producing plant on the market on average having a lower CO₂ efficiency than the highly efficient CCNG plant.

The probabilities for each event two outcomes also have an influence on the timing of the investment. A sensitivity analysis on the probabilities illustrates how a change in the subjective perception of the chances for each outcome changes decisions. That is, changes in the weighting of each column in Figure 9 can change the optimal timing of the investment, e.g., from investment in 2010 to 2013. This is shown in the four columns with transmission high, wind high, and CO₂ low in Figure 9, where the highest column is with investment in 2013. From this observation, we can conclude that certain knowledge of the CO₂ quota price can lead to delay of the investment from 2010 to 2013.

![Figure 9: Illustration of all NPV values for each combination of events and a discount rate 10 %](image)

**3.2 Investor Holding a Portfolio of Investments at the Power Market**

In the previous analysis the investment response was based on an isolated consideration of the power plant. In this part the profitability of the plant is dependent on the effect the plant can have on the income for the rest of the investors portfolio. This distinction is relevant, when individual investments have a possibility to affect the price determination and hence also the profit for existing plants. At the same time the assumption that a new investment decision is dependent on the portfolio effect is dependent on the assumption that no other investor will make the investment and hence affect the portfolio in the same way. That is, the analysis is based on an assumption that there is low competition with regard to investments on the Nordic power market.

From the analysis we find positive revenues with very high positive trends during the time horizon for the portfolio including the new investment as seen in Figure 10.
Figure 10: Yearly cash flow including annualised investment costs without discounting.

But the investment decision depends not on the total profitability for the portfolio, but of the change in the profitability as a result of the new investment (Figure 11).

Figure 11: Difference in average cash flows over events for the portfolio with a combined cycle gas turbine and for the portfolio without the gas turbine for each single year incl. annualised investment costs. Vertical lines indicate possible investment years.

The analysis shows that the change in portfolio income as a result of building the new plant cannot always cover the annualised investment cost in the first period of the time horizon (Figure 11). Therefore, the investor will postpone the investment decision. Furthermore, Figure 11 shows that the influence of the new investment increases with a
negative effect as time goes by. This is caused by the effect of increasing prices that makes the effect of competition relatively larger (see Figure 4).

This opposite effect, compared to the investor without portfolio, also affect the optimal investment decision for the investor, as there are far more negative outcomes, when the investment are considered. Furthermore, this gives the individual event a relatively large influence.

Again, we start with the difference in net present value for each combination of events in order to analyse if there are any dominant strategies. This is illustrated in Figure 12, where positive values indicate a total positive value added to the portfolio when investing, while negative values indicate that even though the investment creates value in itself the value added to the portfolio is negative.

![Figure 12: Illustration of all changes in NPV values for the portfolio for each combination of events and a discount rate 10 %.](image)

The conclusion that can be elaborated from Figure 12 is very different from the one found earlier. First of all, we now have a dominating negative effect from the new investment, even though the investment in itself earns money. There are only one out of four times where it will be beneficial for the investor to invest. Consequently, the decision will be influenced on the subject belief of the probability of each event. Following, there has to be high probability that wind power will not be built, and that the CO₂ quota price will get high in order for the investor to invest. If there is high insecurity, e.g. probabilities around 50 %, it will be beneficial to wait and observe even though it will be optimal to invest in 2008 or 2010 with no insecurity (Figure 12).

Therefore, the optimal decision with a discount rate at 10 % is to wait until 2013, and observe the outcome of all events, and then invest if wind power capacity remains the same, and the CO₂ quota level rises, and does not invest at all in all other combinations. Following, it is not possible to find a dominating strategy, as the decision depends on the subjective belief for the events.
4 Conclusions

The contribution of the present paper is that the result has been quantified for a specific geographical location (the Nordic spot market) through extensive work with an empirical model and through the application of modern investment theory. This paves the way for more detailed considerations, for example, quantification of security of supply, the probability distribution of prices and other timely issues.

The analyses conducted in this paper have illustrated some of the consequences of lack of competition when investing in new capacity in the Nordic power market. This was illustrated by analyses of when investors, with or without existing portfolios in the power market, would invest in a combined cycle gas turbine at 500 MW.

From the analyses it can be concluded that high power prices do not necessarily create new investments. New investments will be highly dependent on the competition between new investors in the market. The more competition the higher the chance of getting new investments when prices are high enough to cover expenses, and hence isolated generates profit. Investors holding an existing portfolio of plants will have a tendency to drive prices up by withholding new investments, and hence create extra revenue for existing plants.

If there is considerable competition with new investments, we have a situation where each investment can be considered alone, as there will always be an investor that takes on the investment if it is solely profitable. The analysis of a single investment shows that the prices would reach a level where a combined cycle gas turbines producing also heat is profitable in 2012, with a price level at approximately 200 NOK/MWh.

We find that the future development of wind power development and level of the CO2 quota price has a significant influence on the profitability of the investment both with and without portfolio considerations. Following, timing of investments can be changed depending on what outcome of the events that are most likely, even though the total investment is profitable on average at an earlier stage in time. Therefore, transparency of political decisions can help create investments earlier in the power market if the competition between investors is sufficient.

References


European Commission (EC), Electricity directive 2003/54/EC


Hirst, E. (2003), Long-Term Resource Adequacy: The Role of Demand Resources, Consulting in Electric-Industry Restructuring, Bellingham, WA.


The Impact of Emissions Trading on the Nordic Energy Systems

Tiina Koljonen* & Veikko Kekkonen, VTT Processes, P.O. Box 1606, 02044 VTT

SUMMARY

The introduction of emissions trading within the European Union (EU) in 2005 and the commitments to the Kyoto agreement have influenced the energy policies of the Nordic countries. In this work, the national energy policies of Denmark, Finland, Norway and Sweden are presented. The possible impacts of the EU emissions trading and Kyoto commitments on the Nordic energy system in the 2005-2020 period have been discussed.

The market prices of electricity are studied using a stochastic electricity price model for the Nordic electricity markets. The important ways to lower CO₂ emissions in the energy sector are fuel changes in the direction of lower net carbon emissions. All the Nordic countries seem to invest on new natural gas fired generating capacities while old coal and oil fired generating capacities are closed down. Finland is investing in new nuclear power while Sweden is phasing out its nuclear plants. In Sweden and Norway, wind power might play an increasing role while in Denmark the share of wind power is already high and it is not assumed to grow significantly. The simulation results of the electricity price indicate that the allowance price level higher than 20 €/t will be needed before remarkable changes in the Nordic electricity system may be observed.

1 Introduction

According to Council Decision 2002/358/EC, the EU (EU 15) has a joint reduction commitment in relation to the Kyoto Protocol’s first commitment period (2008-2012). The EU’s joint commitment has been shared among the member states in an internal burden-sharing agreement. Under this agreement, Denmark is obliged to reduce greenhouse gas (GHG) emissions by 21% in relationship to emissions during the base year 1990. However, negotiations are pending regarding compensation to Denmark in 2006 for the effect of the large electricity imports from Norway and Sweden in 1990. According to the burden-sharing, Finland’s GHG emissions should be settled to the 1990’s level and Sweden’s emissions are not to exceed 1990 emissions by more than 4%. The most important policy instrument in the EU’s common climate strategy is the EU Emissions trading scheme (EU ETS), which was started in 2005. The sectors covered in the EU ETS scheme are all combustion installations with a rated thermal input exceeding 20 MW (except hazardous or municipal waste installations), oil refineries, coke ovens, processing and production of ferrous metals, those mineral industries exceeding a certain capacity (the production of lime, cement, clinkers, glass fibre, ceramic products) and the production of pulp, paper and cardboard. In the Kyoto commitment period, Norway’s greenhouse gas emissions shall not be more than 1 per cent higher than in 1990. Norway has close ties to the EU through the European...
Environmental Agency (EEA) Agreement, and therefore EU’s policies are of major significance to Norway as well.

In the Nordic countries, industrial energy consumption is large due to high energy intensity in, for example, pulp and paper and metal industries. The share of space heating is high in overall energy consumption because of cold climate. However, the overall efficiency in energy production is high, since more than 80% of thermal power is produced in combined heat and power plants (CHP). District heating networks are well developed especially in Denmark, Finland and Sweden.

Denmark, Finland, Norway and Sweden form a common Nordic electricity market. In the Nordic market area, the share of hydropower is more than 50% and the rest is mainly nuclear power and thermal power. For the integrated electricity market to perform and develop, it is of major importance for energy and climate policies to be harmonized. However, there are still differences in the taxation of electricity supply in the Nordic countries. Differences also exist in the taxes and charges on consumption in the Nordic countries.

This paper studies the impact of the EU’s emissions trading scheme on the Nordic energy systems and energy prices. First, the national energy and climate policies of the Nordic countries are described. The interaction of the Nordic energy system and the EU’s emissions trading system is discussed. The impact of emissions trading on the Nordic electricity market prices is studied with a stochastic dynamic programming model developed at VTT. Finally, conclusions on the impacts are discussed.

2 National energy and climate policies of the Nordic countries

Denmark, Finland, Sweden and Norway have been applying active-environmentally oriented energy policies for several decades. Therefore inexpensive reduction potentials have been exhausted in both ETS-sectors and non-ETS-sectors. To fulfill the Kyoto target, further reduction efforts will be necessary in all the Nordic countries.

With full compensation of the large electricity import in 1990, Denmark will be allowed to emit about 60 million tons CO₂ equivalent annually in the 2008-2012 period (Ministry of Environment, 2004). In Denmark, it is assumed that the ETS-sectors will bear most of the reduction burden for the Kyoto period, while the non-ETS sectors’ emissions remain constant. Within the ETS-sector, electricity producer will bear most of the reduction burden. Reduction potential in Danish industry and offshore sector only bears a small amount of the reduction required. The reduction potential of GHG emissions in those sectors is small and industries will have little opportunity to pass on the higher costs of purchasing allowances to product prices, because the markets are international.

According to the most recent inventory information, Finland’s average annual target for the Kyoto period is 76.8 million tons CO₂ equivalent per year. Some of the reduction need can be achieved with non-ETS measures but some of it will have to be arranged by ETS enterprises and energy utilities. Within the ETS-sector, the condensing electricity production will bear the greatest reduction. The energy intensive industries, i.e. oil refining, metal industry, mineral industry, and pulp and paper industry bear a small amount of reduction burden (Finnish Government, 2004).

Sweden’s share of EU’s common undertaking permits will limit the net emissions to 75.0
million tons CO₂ equivalent per year. If Sweden decides to include carbon sinks in forested land, the actual emissions may amount to at most 77.1 million tons. In Sweden, the greatest potential in emission reductions are to be found in the housing and properties sector, and also in the public sector, trade and other services, and in households. Because Sweden’s emissions from energy production are low due to large share of nuclear power and renewable energy, the primary industry makes up relatively large part of the trading sector compared to the situation in most Member states. The Swedish installations exposed to competition from outside the EU are mostly in the pulp and paper industry, iron and steel industry, mining industry and cement industry. Within the ETS-sector, these industries bear a small amount of reduction burden of GHG emissions and the energy sector carries a relatively higher burden (Regeringskanliet 2004).

In Norway, a substantial part of the reduction in emissions is to be brought at the national level. Norway has planned a domestic emissions trading system for greenhouse gases, and measures will be taken in the energy, waste and transport sectors, among others. However, the Norwegian system is also to be linked to the Kyoto mechanisms. Norway’s specific national goals for a shift in energy production are to increase wind generators as well as to increase district heating based on renewable energy, heat pumps and waste heat. Norway is also focusing for the use of hydrogen and natural gas as an energy carrier (Royal Ministry of Foreign Affairs Norway, 2002).

2.1 National allocation plans

In Table 1, the main characteristics of the Danish, Finnish and Swedish national allocation plans for the period 2005-2007 are presented. In Denmark, the final setting of the allowed amounts of emissions in 2006 was taken as the starting point for the national allocation plan (NAP) of CO₂ emissions. In the 2005-2007 period, Danish NAP calls for a total allocation of 15% less (i.e. 6 million tons) than the “business as usual” projections in ETS sectors, with the largest reduction occurring in electricity production. The reduction will amount to 7.4% of overall projected emissions for all sectors, if the emissions from the non-ETS sectors remain constant. In Denmark, further reduction efforts necessary to fulfil its climate obligations will be made primarily in ETS-covered sectors (Ministry of the Environment 2004).

In Finland, the proposed total quantity of allowances is 136.5 million tons, which is about three percent lower than the CO₂ emissions estimated for the period 2005-2007. A permit to also incorporate such installations intended for district heat generation whose rated thermal input is 20 MW or less and form a part of a district heating network, whenever at least one of the installations has an input more than 20 MW (i.e. opt-in).

In Sweden, the planned total quantity of allowances allocated amount on average to 22.9 million tons per year in the period 2005 to 2007. The reduction will amount to about 14% of the projected emissions for ETS sector. Like Finland, Sweden has used the opt-in to include in the trading scheme the combustion installations with a capacity below 20 MW which are a part of a district heating system, where the total installed capacity in the same scheme amounts to at least 20 MW. The allocation to the energy sector is based on the average emission during the years 1998-2001, which are multiplied with a factor 0.8. On the other hand, industries receive an additional allocation based on future emissions from certain industrial processes.
Table 1. Main characteristics of the Danish, Finnish and Swedish allocation plans for 2005-2007.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Denmark</th>
<th>Finland</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allocation method</td>
<td>Historical &amp; benchmark(^1)</td>
<td>Historical &amp; benchmark(^2)</td>
<td>Historical &amp; benchmark(^3)</td>
</tr>
<tr>
<td>Early action</td>
<td>Taken into account generally</td>
<td>Not taken into account</td>
<td>Not taken into account</td>
</tr>
<tr>
<td>Cleaner technology</td>
<td>Taken into account generally</td>
<td>For renewable energy, CHP and industry</td>
<td>For CHP and new entrants</td>
</tr>
<tr>
<td>New entrants</td>
<td>Reserve of 3 million tons</td>
<td>Reserve of 2.5 million tons</td>
<td>Reserve of 1.8 million tons</td>
</tr>
<tr>
<td>Auctioning</td>
<td>5% of the total</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Pooling</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Opt-in/Opt-out</td>
<td>No/No</td>
<td>Yes(^4)/No</td>
<td>Yes(^4)/No</td>
</tr>
<tr>
<td>Changes in taxes and levies</td>
<td>CO(_2) taxes on fuels</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Total/annual number of allowances</td>
<td>100.5/33.5 million tons</td>
<td>136.5 million tons</td>
<td>/22.9 million tons</td>
</tr>
<tr>
<td>Greatest CO(_2) reductions</td>
<td>In electricity production</td>
<td>In electricity production</td>
<td>In electricity production</td>
</tr>
</tbody>
</table>

\(^1\) Base period 1998-2002 with certain exceptions: 2002 emissions are used, if they were higher than in the base period, only operational years are taken into account, benchmarking is used for significant expansions in 2002-2004 and for new installations

\(^2\) Base period 1998-2001 with certain exceptions relating to raw material or process related emissions, benchmarking is used for new entrants.

\(^3\) Base period 1998-2002 for industry, CHP and heat production, 200-2003 for condensing power production, benchmarking is used for new entrants

\(^4\) Combustion installations with a capacity below 20 MW which are a part of a district heating system, where the total installed capacity in the same network amounts to at least 20 MW.

2.2 The impact of energy and climate policies on energy investments

Emissions trading will also change the investment environment. Especially, high CO\(_2\) allowance price levels will favor investments, which are “CO\(_2\)-emissions free” and/or have low specific emissions in energy production. The timing of investment will depend on the development of electricity prices, CO\(_2\) market prices and fuel prices, all of which is difficult to predict. On the other hand, the impact of emissions trading does not only depend on the expected allowance prices, but also on the behavior of the allowance market (volatility, correlations to electricity and fuel prices). Also, the uncertainty regarding the allocation of emission allowances and future political decisions is critical for investment decisions (Laurikka & Koljonen 2005).

In Finland, new nuclear capacity is being built, while the Swedish nuclear power plants are planned to close. Barsebäck 2 nuclear reactor is to be closed before 2010 and the rest after 40 years’ operational lifetime. It is assumed that the phased out nuclear power will be replaced primarily by natural gas based CHP and condensing power plants, and wind
power. An increased use of waste in district heating has also considered. In Denmark, old coal and oil fired plants would be replaced by less CO₂-intensive co-generation plants using natural gas. The largest potential in CO₂ reductions are estimated in CO₂ injection in oil fields and aquifers (Swedish Energy Agency 2004).

Because major hydropower developments are no longer being undertaken, Norway will focus on wind power and also natural gas fired generation. The goal for wind generators is to construct production capacity of at least 3 TWh/year by the year 2010. Gas fired plants may be combined with CO₂ capture also.

3 The interaction of Nordic energy system and the EU CO₂ trading system

In the Nordic electricity markets about 70% of the electricity is renewable or nuclear power. However, because coal condensing power tends to have a dominant position of the production margin during most of the year, market price of electricity will increase due to emissions trading. This will increase the income from electricity produced by renewable energy sources and nuclear power. During dry periods, the shortage of hydropower is compensated by an increase in coal-fired condensing power and import of electricity to the Nordic area. During these dry periods, the annual CO₂ emissions in are at the highest level, especially in Denmark and Finland. On the other hand, the national allocation of emissions rights in Denmark, Finland and Sweden will also affect the market price level of electricity. As described in previous chapter, most of the CO₂ reductions are allocated to energy producers. During dry seasons and cold winters, the market price level of electricity might increase considerably due to shortage of free emission allowances.

It is assumed that the additional costs for the energy sector are finally transferred to the energy users, like energy consuming industries, households, agriculture, and service sectors. This cost increase may be considerable for those companies, which produce energy intensive products. For some industries it might be more profitable to reduce production volumes and sell emissions rights, if the allowance price level is high enough. In the Nordic area, there are a lot of pulp and paper, metal and minerals industries as well as oil refining. The national allocation of emissions rights will influence the direct costs of emissions trading within these sectors.

High CO₂ price levels will increase the demands and market prices of those fuels, which net carbon emissions are lower. Oil and coal will be replaced by natural gas and, on the other hand, peat will loose its competitiveness relative to biomass in Finland and Sweden. In the open markets, the price of natural gas is generally based on the cost of alternative fuel that would be payable by the customer. In most agreements, the price of natural gas is indexed against the price of oil and in some cases against the price of coal or quoted price of electricity. It is likely that high CO₂ price levels would affect natural gas prices, especially in the long run. In Finland and Sweden, biomass raw material is also utilized in pulp and paper sector, which would suffer from the rising price of wood fiber.

4 The impact of emissions trading on Nordic
electricity prices

The impacts of emissions trading on the Nordic electricity market prices were studied with a stochastic dynamic model, which minimizes the variable costs of electricity production to cover the demand for electricity in the Nordic area including Denmark, Finland, Norway and Sweden. In the model, the electricity demands and supplies are specified for each country. The model includes imports to Nordic area and exports from Nordic area as well as constraints in their transmission capacities. The model calculates system price of electricity, i.e. transmission constraints inside the Nordic area are not included in the model. The assumed market price of the emissions allowance is added to the marginal costs according to the amount of CO2 emitted. This means that installations that utilize fossil fuels with a high carbon content and have low energy conversion efficiencies will produce large amounts of CO2 and will, therefore, be most affected by emissions trading. Figure 1 shows an example of the simulation result for a distribution of an equilibrium price of electricity concerning the year 2005. Here, the normal annual rainfall and the market price of 10 €/t CO2 were assumed. It should be noted that the market price may be significantly higher than the equilibrium price.

Figure 1. Stochastic simulation of the weekly equilibrium price of electricity starting from the beginning of 2005. An average hydropower production is assumed. The price of emission allowance is 10 €/t CO2 in the case presented.

4.1 Input values for scenario calculations

Table 2 shows the demand scenarios for each country, which are based on the estimates by national authorities for Denmark, Finland and Sweden. Norway’s electricity demands are published by Statnett (Statnet, 2003).
The assumed changes in production capacities are shown in Figure 2. The capacity changes have been collected from the national reports of the Nordic countries (Energistyrelsen, 2003; Finnish Government, 2004; Regeringskansliet, 2004; Statnet, 2003). New nuclear plant will be operational in 2009 in Finland and Barsebäck 2 would be closed in Sweden before 2010. We have also assumed that in 2010-2020 period, old nuclear capacities will be closed down in Sweden (i.e. Oskarhamn and Ringhals). On the other hand, we have also assumed that some nuclear capacity will be operational in Sweden in the period 2015 to 2020. In the long term, the highest increases are assumed in wind power capacities in Sweden and Norway. New condensing as well as combined heat and power (CHP) capacity would be based on natural gas. In Denmark, old oil fired generating capacities will be closed down. Therefore we have assumed that also new coal fired CHP will be built in Denmark.

![Figure 2. The assumed changes in the electricity generating capacities in the period 2005-2020.](image)
In different scenarios we have varied the yearly average hydropower production, the market price of CO₂ allowance, the fuel prices and the production capacities in 2005, 2010, 2015, and 2020. The base scenario called “normal” represents a situation where an average hydropower production as well as relatively low fuel and CO₂ prices have been assumed. In the scenarios “dry” and “wet” the yearly hydropower production is decreased or increased by 15% of the yearly average. In the scenario “CO₂seq” we have considered that the new coal fired CHP plants in Denmark as well as the new natural gas fired CHP plants in Norway will be equipped with CO₂ capture and storage plant in the 2015-2020 period. Because Norway is not participating EU’s emissions trading scheme, we have also assumed that Norway will not pay for emissions allowances before the post Kyoto period in 2015 and 2020.

Table 2 shows the assumed price scenarios for energy resources and CO₂ allowance of the base scenario. The fossil fuel prices (raw oil, natural gas, coal) are based on the forecasts by International Energy Agency (IEA 2004). The other price scenarios follow the price trends of fossil fuels.

Table 2. The price scenarios for fuels (€/MWh fuel), for power exchange (€/MWh electricity), and for CO₂ allowance (€/t).

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy fuel oil</td>
<td>16</td>
<td>16</td>
<td>14</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>Natural gas</td>
<td>14</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Coal</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Peat</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Biomass</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>CO₂ price</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

4.2 Scenario results

Table 3 shows the simulation results of the yearly average market price of electricity. In our simulations, the new nuclear capacity in Finland lowers the market price of electricity in 2010. After that the price of electricity raises again due to shut down of old generating capacities including Swedish nuclear capacity and, on the other hand, increasing demands. It is shown that the assumed availability of hydropower has the greatest impact on the electricity price. In 2005, the marginal producer is coal condensing power. In 2010, the natural gas condensing power in Norway seems to be more competitive than coal fired condensing power, because we assumed that Norway will not pay for CO₂ allowances. With allowance price level 20-30 €/t, natural gas condensing power seems to be more competitive than coal fired condensing power in the other Nordic countries also. However, electricity production with coal fired CHP still seems to be competitive. CO₂ sequestration seems to be very competitive especially in coal fired generation.
Table 3. Simulation results of the average yearly equilibrium price of electricity for different scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Normal</td>
<td>27.7</td>
<td>23.2</td>
<td>30.1</td>
<td>37.5</td>
</tr>
<tr>
<td>2. Dry (-15%)</td>
<td>40.0</td>
<td>35.3</td>
<td>39.0</td>
<td>47.2</td>
</tr>
<tr>
<td>3. Wet (+15%)</td>
<td>16.9</td>
<td>15.3</td>
<td>20.6</td>
<td>25.9</td>
</tr>
<tr>
<td>4. Allowance 0 €/t</td>
<td>21.6</td>
<td>19.1</td>
<td>25.8</td>
<td>29.6</td>
</tr>
<tr>
<td>5. Allowance +10 €/t</td>
<td>32.1</td>
<td>26.7</td>
<td>33.6</td>
<td>40.9</td>
</tr>
<tr>
<td>6. Fuel prices +30%</td>
<td>32.0</td>
<td>28.9</td>
<td>36.4</td>
<td>44.3</td>
</tr>
<tr>
<td>7. CO₂ seq. in 2015</td>
<td>27.7</td>
<td>23.2</td>
<td>30.4</td>
<td>37.2</td>
</tr>
</tbody>
</table>

5 Conclusions

EU’s emissions trading has influenced the national energy and climate policies in Denmark, Finland and Sweden. According to the national allocation plans of these countries, the ETS-sectors will bear most of the reduction burden. Within the ETS-sector, electricity producers will bear most of the reduction burden.

According to the simulations of the Nordic electricity markets, the assumed availability of hydropower has the greatest impact on the electricity price. During the dry seasons, very high electricity prices may be expected, especially with high CO₂ price levels. On the other hand, high electricity and CO₂ price levels will favor investments, which have low specific emissions in energy production. Denmark and Norway have a possibility to include CO₂ sequestration in the production units, which seems to be competitive in the long term. In all the Nordic countries it is assumed, that the phased out capacities will be gradually replaced with natural gas based CHP and condensing power plants.

6 References


Laurikka H. & Koljonen, T (2005). Emissions trading and investment decisions in the


Impacts of Wind Power in the Nordic Electricity System in 2010

Peter Meibom¹, Rüdiger Barth², Heike Brand², Christoph Weber³

¹Corresponding author, Risø National Laboratory, Frederiksbergvej 399, DK-4000 Roskilde, tel. 4677 5119, Fax: 4677 5199, e-mail: peter.meibom@risoe.dk
²IER, University of Stuttgart, Germany.
³Chair for Energy Management, University of Duisburg-Essen, Germany

Abstract

The technical and market impacts of introducing large amounts of wind power in the North European Electricity System in 2010 are analyzed using a large, stochastic, partial equilibrium model. The model has been developed in the EU-funded research project WILMAR. It covers Denmark, Finland, Germany, Norway and Sweden, and explicitly takes the distribution of wind power production forecast errors into account when making dispatch decisions for the power plants in the system. One scenario for the development of the production capacity especially the installed wind power capacity, from now to 2010 are set up and analyzed with the model. Results using a preliminary version of the model for a Nordic case covering only one week are presented. They show that increased wind power production replaces hydro power production such that the avoided costs due to the increased wind power production depend very much on the value of increasing the amount of water stored in hydro reservoirs.

1 Introduction

Due to the fast growth of installed wind power capacity especially in Denmark, Germany and Spain, and the expectations of continued high growth rates in the future, the technical and economic impacts of introducing fluctuating wind power production in power systems have attracted increased attention in recent years. Recently a large German study has been published that analyses the impacts, especially the grid requirements, of increasing installed wind power capacity in Germany with 21.5 GW in the period 2004-2015 (DENA 2005).

The Wilmar project is part of this effort going on in several countries aimed at understanding and quantifying the technical, economic and environmental impacts of increased wind power production. Wilmar is an acronym of “Wind Power Integration in Liberalised Electricity Markets”. The project was started in 2002 and is funded by the EU’s 5th Research programme on energy and environment. Risø National Laboratory is co-ordinator of the project and partners include SINTEF, Kungliga Tekniska Högskola, University of Stuttgart, VTT, Nord Pool Consult, Technical University of Denmark, ELSAM A/S and Elkraft-System A/S.

The aim of the Wilmar project is to investigate the technical and economical consequences of large-scale deployment of fluctuating, renewable sources and to develop a modelling tool that can handle system simulations for a larger geographical region with an international power exchange.
The main methodological focus of the Planning Tool is to include information contained in wind power production forecasts in the decision support tool. Recently the work with wind power production forecasting has been extended from only aiming at forecasting the expected wind power production to forecasting a distribution of future wind power productions. By using stochastic optimisation in the Planning Tool the distribution of wind power production forecast errors are taking explicitly into account when making dispatch decisions for the power plants in the system, i.e. the dispatch decisions are more robust towards wind power production forecast errors than decisions taken with a model not using stochastic optimisation.

The design of the Planning Tool has been presented in several conference presentations previously (Brand et al 2005; Barth et al 2004; Meibom et al, 2004, Brand et al. 2004)* and will therefore only briefly be described in this paper. Instead an application of the Planning Tool being used to analyse the impacts of wind power production in the Nordic countries except Island in 2010 is presented. The next section gives an overview of the Planning tool. Section 3 presents the main assumptions in the scenario for the Nordic power system in 2010, and section four presents the results.

2 Overview of the Planning Tool

An overview of the design of the Planning Tool is given in Figure 1. The Planning Tool consists of three databases, three sub-models† and a User Shell. Below the functionality of the three models is briefly explained.

Long-term model

Due to the existence of hydro reservoirs and limitations on the amount of water inflow to the hydropower system, the use of hydropower must be optimized over a one-year (or longer) horizon. Furthermore, if we assume the existence in the model of a fixed CO₂ quota for the North European electricity system, the CO₂ emissions from the power plants will be subject to a long-term (yearly) restriction.

The Long-Term Model will optimize the use of water inflow and CO₂ quotas over a one-year horizon. The input from the long-term model to the Joint Market model will be one table with the water values (opportunity costs of using stored water) as a function of reservoir filling and time of year, and another table with the CO₂ shadow prices as a function of the fraction of the available CO₂ quota still not used and the time of year.

The Long-term model gets input data from the Planning Tool Input database and delivers output to the Planning Tool output database (see Figure 1). The sharing of input data between the Joint Market model and the Long-term model secures consistency between the models with regard to input data.


† The Scenario Tree Matlab module is counted as one sub-model, because the sub-models constituting this module are all written in MatLab and have been merged into one.
Joint Market model

The model includes markets for three types of products: day-ahead market power, district and process heat, and regulating power. The model optimizes the unit commitment and dispatch taking into account the trading activities of the different actors on the different energy markets. Additionally different restrictions such as transmission constraints or capacity constraints of the power and heat generating units are taken into account. An approximation for modelling minimum operation times and minimum shut down times in a linear way is included into the model definition. The proposed market model is defined as a stochastic linear programming model. The stochastic part is presented by a scenario tree for possible wind power generation for the different hours.

In stochastic multi-stage linear recourse models, there exist two types of decisions: decisions that have to be taken immediately and decisions that can be postponed. The first kind of decisions are called “root” decisions, as they have to be decided “here and now” and before the uncertain future is known. The second kind of decisions is called “recourse decisions”. They are taken after some of the uncertain parameters are known. With these “recourse decisions” actions can be started which might possibly revise the
In the case of a power system with wind power, the power generators have to decide on the amount of electricity they want to sell at the spot market before the precise wind power production is known (root decision). In most European countries this decision has to be taken at least 12-36 hours before the delivery period. And as the wind power prediction is not very accurate, recourse actions are necessary in most cases when the delivery period is in the near future (recourse decisions).

In a liberalized market environment it is often possible not only to change the unit commitment and dispatch, but even to trade electricity at the hour-ahead market. In this extended model three electricity markets and one market for heat are included in the planning model:

1. A day-ahead market for physical delivery of electricity where the Elspot market at Nord Pool is taken as the starting point. In the following, this market is called the day-ahead market.

2. An intra-day market for handling deviations between expected production and consumption agreed upon on the day-ahead market and the realized values of production and consumption in the actual operation hour. Regulating power can be traded up to one hour before delivery at the intra-day market. Flexible producers offer regulating power at this market. In our model the demand for regulating power is caused by the forecast errors connected to the wind power production.

3. A day-ahead market for automatically activated reserve power (frequency activated or load-flow activated). The demand for these ancillary services is determined exogenously to the model. This market will be called the ancillary services market.

4. Due to the interactions of CHP plants with the day-ahead and intra-day market, a market for district heating and process heat is included in model.

**Scenario Tree Matlab module**

The inclusion of the uncertainty about the wind power production in the optimization model is considered by using a scenario tree describing the wind power production in the different regions. The generation of a scenario tree containing correct forecast errors of wind power production depending on the forecast horizon and containing the correct correlations between forecasted wind power production in different regions is a complicated task. The construction of this scenario tree is carried out in two steps:

A. Generation of stochastically drawn wind power production scenarios.

B. Reduction of the scenario tree.

An important source of data is a database containing historical forecast errors of wind speed forecasts. The errors between the wind speed forecasts and the real wind speed can be quite large. So it is of crucial importance to include prediction errors in the model. Since the errors increase with the length of the forecast period, the so called “Wind Speed Forecast Error Module” (Söder, 2004) assumes a multidimensional ARMA time series for this forecast error for each wind speed measurement station additionally taking into account the correlation between different stations.

The ARMA time series contain the usual error terms. These are simulated by Monte Carlo Simulations resulting in a large number of scenarios for the forecast error. In order to obtain for each region the forecast of the wind power from the wind speed forecast, technological aspects of the wind power stations located in the considered region are needed. Additionally, their spatial distribution within each region has to be taken into
account yielding an aggregation of the power generation in each region.

In order to keep computation times small for models representing an international market with a huge number of generating units, only significantly less scenarios than the scenarios created by Monte Carlo simulations can be used. Therefore a stepwise backward scenario reduction algorithm based on the approach of Dupacova et al. (2003) is used.

3 Application

We study the consequences of increasing the installed capacity of wind power in the Nordic power system with 3243 MW in the period 2005-2010. Our starting point is the configuration of the Nordic power system in the end of 2004. The assumed development in new power production capacity in the period 2005-2010 is shown in Table 1. The increase in installed wind power capacity is shown in Figure 2. No decommissioning of existing power plants is assumed except for the Swedish nuclear power plant, Barcebäck 2, with 600 MW shut down from the start of 2006, and the decommissioning in Eastern Denmark shown in Table 2. The transmission capacities are assumed constant from 2004 to 2010.

The Nordic countries are assumed to have the same fuel prices except for natural gas. The scenario for the development of fuel prices in the period 2004-2010 is delivered from Elkraft System. For coal, oil and natural gas the fuel price scenario is based on IEA prognosis, *World Energy Outlook 2004*, which describe a very moderate development in fossil fuel prices. The natural gas price applies for Denmark and Finland. Swedish power plants are assumed to pay 10% more and Norwegian power plants 10% less than the Danish price. Figure 3 shows the assumed development in fossil fuel prices in the period 2001-2010.

We assume a CO₂ emission permit price of 15 Euro2002/Ton CO₂.

<table>
<thead>
<tr>
<th>Type</th>
<th>Denmark</th>
<th>Norway</th>
<th>Sweden</th>
<th>Finland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Nuclear</td>
<td>None</td>
<td>None</td>
<td>Upgrading with 550 MW in 2008</td>
<td>1600 MW in 2010</td>
</tr>
<tr>
<td>Other thermal</td>
<td>None</td>
<td>600 MW NGCC in 2009</td>
<td>260 MW NGCC in 2007. 410 MW NGCC in 2010</td>
<td>None</td>
</tr>
<tr>
<td>Wind power</td>
<td>+975 MW</td>
<td>+975 MW</td>
<td>+875 MW</td>
<td>+418 MW</td>
</tr>
</tbody>
</table>

*Table 1: New power production capacity in the Nordic system in the period 2005-2010.*
Figure 2 Installed wind power capacity in the end of year 2004 and 2010.

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Shut down year</th>
<th>Fuel</th>
<th>Power capacity [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.C. Ørsted Værket, Rest</td>
<td>2006</td>
<td>Natural gas</td>
<td>155</td>
</tr>
<tr>
<td>Svanemølle Værket, Rest</td>
<td>2007</td>
<td>Natural gas</td>
<td>75</td>
</tr>
<tr>
<td>Asnæsværket 4</td>
<td>2006</td>
<td>Coal</td>
<td>270</td>
</tr>
<tr>
<td>Stignæs Værket 1</td>
<td>2006</td>
<td>Coal</td>
<td>143</td>
</tr>
<tr>
<td>Amager Værket 1</td>
<td>2004</td>
<td>Coal</td>
<td>136</td>
</tr>
</tbody>
</table>

Table 2 Assumed shut downs in Eastern Denmark in the period 2004-2010 based on E2 announcements (Wittrup 2004).

Figure 3 Fuel price scenarios for fossil fuels except uran.
4 Results

Figure 4 The expected wind power production sold at the day-ahead market and the realized wind power production in the actual operation hour in Eastern Denmark.

Figure 5 The electricity prices on the Dayahead market and the Intraday market in Eastern Denmark

Results are presented for week number 18 in 2010. Figure 4 shows the expected wind power production (average over the wind power production scenarios in the scenario tree) and the realized wind power production in Eastern Denmark. The expected wind
power production is sold on the Dayahead market. The circle in the figure indicate hours where first the expected production is higher than the realized wind power production such that increased production from other units are required in the actual production hour, and next the opposite situation occurs requiring down regulation of production from other units in the actual operation hour.

Figure 5 shows the electricity prices on the Dayahead and the Intraday market in Eastern Denmark. The circle points out the same hours as in Figure 4. When up regulation of production is required, the Intraday price becomes higher than the Dayahead price as seen in Figure 5. Likewise in the case of down regulation the Intraday price is lower than the Dayahead price. The model therefore gives the expected price reaction on the Intraday market relatively to the Dayahead market to the forecast error in the wind power production. The price difference between the Dayahead and the Intraday market is the marginal regulation costs in the operation hour in question.

Having a model that can calculate the costs of regulation due to forecast errors in the wind power production is a large step forward compared to deterministic models. For example the value of increasing the precision of wind power prediction tools or the revenue of dedicated wind power integration measures such as e.g. electricity storages both will depend heavily on the price differences between the Dayahead and Intraday market.

A first step in the evaluation of the costs and benefits of wind power production is to calculate the avoided costs in the rest of the power system due to the wind power production. Here we compare two simulations of the Nordic power system in week 18 in 2010 only differing in the amount of installed wind power production. The two cases have installed wind power capacity as shown in Figure 2, i.e. corresponding to installed wind power capacity in the end of 2004 and end of 2010, and are named Wind2004 and Wind2010. So we are analyzing the avoided cost due to the installed wind power capacity in the Nordic power system in the period 2005-2010. The costs compared in the two cases consist of variable production costs (fuel, O&M and start/stop), variable transmission costs (loss), and the change in value due to a change in the amount of water stored in hydro reservoirs.

In week 18, 288 GWh additional wind power production exist in Wind2010 compared to Wind2004. The wind power production mainly displaces hydro power production, such that the evaluation of the saved production costs become very dependant on the value associated to changes in the filling degree in hydro reservoirs. This value often termed the water value is calculated in a preliminary version of the Long term model to 17.5 Euro2002/MWh. The saved production costs in the rest of Nordic power system due to the additional production of wind power therefore become 17 Euro2002/MWh wind power production. This corresponds more or less accidentally quite well with the values estimated in the previously mentioned DENA study, which give values of 17-21 Euro/MWh wind for a German case in 2010 (DENA 2005).

5 Conclusions

The application presented in this paper indicates the results achievable with the use of the Planning Tool developed in the Wilmar project. The model calculates price reactions on the Dayahead and the Intraday market due to wind power production, and the change in production patterns of the rest of the units in the power system as wind power
production is increased. Having a model that takes the stochastic nature of wind power production explicitly into account when making dispatch decisions is beneficial when analyzing a number of the problems connected to integration of wind power production, notably the costs and necessary amounts of regulation power due to wind power production. The design of the Planning tool is nearly completed, and in the coming months the tool will be used to more thorough analysis of the integration costs of wind power and the performance of dedicated integration measures. The Planning tool will be made publicly available on www.wilmar.risoe.dk in the end of 2005.

References


Session 16 – Systems Analysis

Chairman: John M. Christensen, UNEP Risø Centre, Denmark
The Use of Biological Systems to Improve the Energy Sustainability

G Giovannozzi-Sermanni
Agrobiol Agrochem Dept
Tuscia University Viterbo (Italy)

Abstract
Few considerations on the possible role of biochemical reactions to improve energy availability for the mankind activities are presented.
An improvement of the sustainability, among many biological cycles, can be obtained by amplified organic matter biosynthesis and its efficient utilisation.
In the plants the increase of biosynthesis of cellulose, lignins, starch and hemicelluloses, main renewable reserves of chemical bonds in the biosphere, can be meliorated by more active photosynthetic cycle due to phosphoenolpyruvic carboxylase.
A second aspect is related to the efficient biodegradations of the plant organic matter by cellulases, hemicellulases and polyphenol oxidases allowing the mobilisation and utilisation of huge amounts of chemical bonds.
The capability of this biodegradation can be improved by an emerging technology, the solid state fermentation (SSF), with which the biodegradation is controlled and driven
An example of such integrated approach is constituted by paper pulps from agricultural and forestry materials obtainable with less chemicals use, lower specific energy, better yield of paper pulps and better properties of the papers.

Introduction
A wide variety of products and processes are needed for the current activity of human society and they affect the sustainability seen as a balance between available and requested energy.
As well known, the supply of renewable energy necessary for the life is obtainable only from the solar light by means of photosynthesis with the production of two coenzymes, ATP and NADPH, key compounds for the beginning of the biosynthesis of organic matter (fig1).

Fig 1
Transformation of light energy in chemical bonds
Under this light the sustainability, depending on the photosynthesis, can be improved by increasing the photosynthetic efficiency and by a good efficient utilisation of the chemical energy of organic matter.

Agriculture and forestry represent the largest human intervention, and the improvement of the carbon dioxide assimilation and of the biomass utilisation, so that the harvest index can rise high values, may have great effect not only on advances of the biotechnological approach but also on economic accounting.

**Efficient biosynthesis of organic matter**

With NADPH, ATP and carbon dioxide the carbohydrates biosynthesis is started.

The most abundant organic molecules produced by green cells are celluloses, lignins hemicelluloses and starch which constitute hence huge renewable reserve of chemical energy in the Planet. Anyway their biological utilisation, which can be the basis for energy finalities (fig 2), can be more enhanced, so that improved carbon dioxide absorption and controlled organic matter utilisation are suitable modes for the improvement of the sustainability.

![Diagram of carbon utilisation of plant materials](image)

**Fig 2**

Main carbon utilisation of plant materials

The carbon dioxide is absorbed through stomata with different rates following the water availability. As described largely in scientific literature in case of drought (14, 17, 18) the plants close the stomata and save water as happens in arid climates so that the utilisation of carbon dioxide decreases.
Nevertheless the plants are able to force the carbon dioxide absorption by an enzyme which has great affinity with carbon dioxide: the phosphoenolpyruvic carboxylase (PEPC) which utilises phosphoenolpyruvate to produce oxalacetic acid and then malic acid which constitutes a reserve of carbon dioxide for the photosynthetic Calvin cycle (fig 3).

![Figure 3](image1.png)

**Fig 3**
Dark fixation of carbon dioxide

In this way the photosynthesis is maintained at acceptable levels even in drought conditions and it is possible to metabolise the same carbon dioxide amount with less water consumption (fig 4).

![Figure 4](image2.png)

**Fig 4**
Phosphoenol pyruvic carboxylase to improve the water use.

Therefore an increased PEPC activity is important for a better utilisation of sun light and such biochemical cycle determines different photosynthetic efficiency defined as C3, C4, CAM plants growing in temperate, warm and arid climates respectively. Therefore by using species more rich in phosphoenolpyruvic carboxylase, usually herbaceous plants, the water needs are decreased, even if the production of organic matter is the same.
Efficient utilisation of chemical bonds

Keeping in mind that the chemical bonds of lignocellulosic biomass can be used for the biosynthesis of numberless organic compounds, for a good efficiency, an initial vigorous biodegradation by few enzymes is necessary to obtain soluble molecules, substrates for the metabolism of cells (fig 5.)

![Fig 5](image)

**Fig 5**
Fundamental role of hydrolytic and oxyreductive enzymes for lignocellulose utilisation

In fact the bioconversions generate water soluble copolymers (SLC), and by gel filtration it can be shown that these copolymers are successively degraded by cellulases, xylanases and laccases (Fig 6) (2,3,6,10,12,15,16).

![Fig 6](image)

**Fig 6**
Gel filtration of soluble lignocelluloses (SLC)

Such biodegradation can be obtained and optimised by using solid state fermentations (SSF) a developing technology which allows to employ directly insoluble agriculture and forestry materials as substrates for foods, feeds, fibres, fuel, ethanol, chemicals etc.
With SSF bioreactor, like the first one described in scientific literature (fig 7), it has been ascertained that, for reproducible and efficient SSF, it is proper to work in sterile conditions, by controlling temperature and inner atmosphere of the bioreactor, by employing different species of fungi or bacteria. It is remarkable that SSF is characterised by the highest possible substrate concentration, high selectivity, mild operating conditions, absence of large amounts of water due to the absence of free water, no large quantities of liquid waste to dispose off, better efficiency, less cost if compared to the submerged fermentation.

Therefore with SSF (11,13) it is possible to degrade efficiently insoluble lignocelluloses but, when the SSF is used for large amounts of lignocellulose there is a rise of temperature due to biological activity of the microorganisms. Such effect is due to the scarce heat transfer being organic matter a poor heat conductor, and to improve the transfer of biological heat and to maintain the right temperature, a rotary drum bioreactor equipped with a cooling jacket can be used (fig 8, 9).
An example of the application of these biochemical reactions is given by the utilization of C4 plant as sorghum or corn to obtain cellulose fibres.

Laccase, Mn peroxydases, hemicellulases, useful enzymes to obtain cellulose fibres, can be produced by SSF of plant residues.

With these enzymes, by utilising corn stalks, sorghum (C4 plant), cereal straws (C3 plant), kenaf, or any other agricultural residue, paper pulps are obtained with the reduction of 50% of the specific energy, of 30% of the alkali request if compared with usual processes. Also the freeness, the burst index, the tear index, the Gourley porosity and other technical characteristics of obtainable papers are improved (4, 5, 7, 8, 9).

Therefore such biochemical reactions concerning a more active organic matter biosynthesis and an improved biodegradation for the production of paper pulps seem to be a reasonable example of the role of the biology to develop processes saving energy and maintaining more easily the balance of renewable energies.
Conclusions

The scientific and technical approaches all over the world to control almost partly the energy balance in the life sphere are innumerable so that is almost impossible summarise them shortly. Nevertheless many sectors can be interested by biochemical reactions to obtain substrates, fuel, fine chemicals etc. A better capture of sun light by photosynthesis, due to higher PEPC activity, and a better utilisation of the enormous quantity of plant materials such as agricultural residues or specialised crops, seem to be a couple of biochemical aspects leading to a better sustainability.

References


2) The biodegradation of aromatic compounds by a white-rot fungus and related applications. Giovannozzi-Sermanni, Giovanni; D'Annibale, Alessandro; Crestini, Claudia; Stazi, Silvia Rita. Recent Research Developments in Biotechnology & Bioengineering (1998), 1(Pt. 2), 191-202.

3) Structural modifications induced during biodegradation of wheat lignin by Lentinula edodes. Crestini, Claudia; Sermanni, Giovanni Giovannozzi; Argyropoulos, Dimitris S Bioorganic & Medicinal Chemistry (1998), 6(7), 967-973


9) Characteristics of paper handsheets after combined biological pretreatments and conventional pulping of wheat straw. Giovannozzi-Sermanni, Giovanni; D'Annibale, Alessandro; Perani, Claudio; Porri, Antonio; Pastina, Francesco; Minelli, Vincenzo; Vitale, Nicoletta; Gelsomino, Antonio. Tappi Journal (1994), 77(6), 151-7

10) The production of exo-enzymes by Lentinus edodes and Pleurotus ostreatus and their use for upgrading corn straw. Giovanni Giovannozzi; D'Annibale, Alessandro; Di Lena, Gabriella; Vitale, Nicoletta Silvia; Di Mattia, Elena; Minelli, Vincenzo Bioresource Technology (1994), 48(2), 173-8.


Session 17 – Resources and Markets in Developing Countries

Chairman: Mogens Arndt, Energi E2, Denmark
BIOFUELS: THE KEY TO INDIA’S SUSTAINABLE ENERGY NEEDS

Linoj Kumar*
M P Ram Mohan*

*Research Associate,
The Energy and Resources Institute (TERI)
Lodhi Road, New Delhi, India – 110003
Tel: 91 – 11 – 24682100/11
Email: linoj@teri.res.in

ABSTRACT

A country of billion population and having seen a sustained and rapid economic expansion in the last decade India’s energy demand will see a quantum 40 percent growth in the next ten years. India, like many other developing countries, is a net importer of energy. More than 25 percent of primary energy needs are being met through imports mainly in the form of crude oil and natural gas. Biofuels as a domestic and renewable energy source, can significantly reduce India’s dependence on foreign oil, can minimize the environmental threat caused by the fossil fuels and it is the best ever alternate in securing the energy needs of the country. The other advantage is in meeting rural energisation and empowerment of village community through enhanced livelihood opportunities and thus controlling migration.

There is a huge potential in India for the production of biofuels in terms of feedstock availability. Present accessibility of feedstocks in meeting the demand of biofuels has been examined along with recent developments in the biofuel sector of the country. Commercialisation of biofuels has to overcome various technological and policy challenges. Keeping this perspective in view biofuel technologies has been evaluated in terms of logistics of feedstock availability, existing processes, and policy framework. Obstacles for biofuel promotion are dealt in detail and a viable model for India is proposed. Research priorities that need to be promoted on an urgent basis to improve the economic competitiveness of biofuels has been identified and scrutinized. It is concluded that through a coherent and responsible policy and technological initiative, India could meet the every growing energy need through biofuels creating a positive impact on energy economy of the country.

INTRODUCTION

1.1. Indian Energy scenario and Significance of Biofuels

India ranks sixth in terms of energy demand accounting to 3.6% of total global energy demand. While the energy demand is expected to grow at 4.8% a year, a large part of India’s population, mostly in the rural area, doesn't have even access to it (8, 16). India still has about 96, 000 villages to be electrified and only about 45% of 138 million households in 583,000 villages use electricity for lighting (8, 20). Most rural kitchens use biomass fuels in smoky kitchens. Inadequate access and poor quality of energy services continues to be a very critical dimension of rural poverty in India.
Further more, being the second most populous country with rapidly urbanizing economy, our dependence on oil import will increase enormously in the near future. In 2003-04, India, which is 70% import dependent for meeting its crude oil requirement, spent 18.36 billion dollars (Rs 84,236 cores) on importing more than 90 million tones of crude oil. It is predicted that if India continues at this rate, we would be consuming 5.6 million barrels of oil /day by 2030 out of which more than 94% will be met through oil imports (8). When we reach that level, we would become major importers in the global oil market and any fluctuation in price or any problems that affect continuous supply can hit our economy very badly. The greatest increase in energy demand occurs in the transportation sector where more than 95% of the demand is met by fossil fuels, which contributes to environmental impairment to a momentous level. In fact, increased environmental degradation do remind that our ways to meet energy demand should be designed as an element of sustainable development as well. For that reason, it is learnt from the present scenario that extreme dependence on petroleum as a primary energy source will entail considerable risks both from energy security and environmental point of view.

Securing long term supply of energy sources requires not only that existing fuel resources be utilized as economically as possible but also that the energy sources used in this fuel system must be diversified. In the coming years, we have to be at a point in our development, where the nation is less dependant on fossil fuels for our energy generation. Keeping this point in view, biofuels are recognized as a major player for ensuring energy security in the future of our country. Recent developments have made these green fuels economically interesting in view of the resource potential and the possibility of improving environmental performance, along with employment generation and empowerment of the rural economy. However Development of biomass-based energy would ensure that new technologies and policies available to keep pace with society’s need for this clean and viable alternatives.

With regard to the fuel guzzling transportation sector, National Auto Fuel Policy, 2003, will be having a revolutionary impact on the social economic and
environmental sector of the country. The main objective is to substantially reduce the massive pollution problems rooted by the vehicular emissions. Broadly, the policy gives a roadmap for achieving various vehicular emission norms over a period of time and the corresponding fuel quality upgradation requirements. Though, policy does not recommend any particular fuel/technology for achieving the desired emission norms, it proposes liquid fuels as the main auto fuels throughout the country and the use of CNG/LPG be encouraged in cities affected by higher pollution levels (7). But both CNG and LPG are in short supply domestically and over the next decade; India’s demand for natural gas and LPG will outstrip the country’s ability to produce it. Therefore the policy tells that commercialization of biofuel vehicle is one of the main ways to reduce energy dependence, financial strain on heavy foreign exchange and environmental issues.

1.2. Initiatives from Indian Government

Keeping in mind these possibilities, Government of India has initiated various policies to give an effect to the early implementation of the biofuels program. These are;

1.2.1 Gasohol Programme
The vision for development of the biofuels sector has already made headway in India. With a view to give boost to agriculture sector and reduce environmental pollution, Government of India have been examining for quite some time supply of ethanol-doped-petrol in the country. In order to ascertain financial and operational aspects of blending 5% ethanol with petrol Government had launched three pilot projects in different states during 2001 and these pilot projects have been supplying 5% ethanol-doped-petrol only to the retail outlets under their respective supply areas. While the Society for Indian Automobile Manufacturers (SIAM) has confirmed the acceptance for use of 5% ethanol-doped-petrol in vehicles. State Governments of major sugar producing States and the representatives of sugar/distillery industries have confirmed availability/capacity to produce ethanol. Government have set up an Expert Group to examine various options of blending ethanol with petrol including use of Ethyl Tertiary Butyl Ether (ETBE) in refineries. Considering the logistical and financial advantages, this Group has recommended blending of ethanol with petrol at supply locations (terminals / depots) of oil companies. In view of the above, Government have now resolved that with effect from 1-1-2003, 5% ethanol-doped-petrol will be supplied in the nine States and four Union Territories.

1.2.2 National Mission on Biodiesel
The planning commission of India has proposed a ‘National Mission on biodiesel’, which is expected to lay a strong foundation of an integrated biofuels production capability in the country. The programme aims to produce enough seeds for the production of biodiesel in sufficient quantities to enable its blending with diesel to the extent of 20% (19). While there is a number of non-edible oil seed producing species in India scattered all over the country the seed collected is being used by the rural communities. It is not available for an organized Programme of biodiesel production. It is clear that any such Programme is based on additional plantation. As a part of national mission on biodiesel it is proposed to take up a demonstration project which will lay a foundation of a self sustaining Programme of plantation and
non edible oil trans esterification to produce enough biodiesel so as to meet the blending requirements within the stipulated period.

1.2.3 Biofuels for Rural Empowerment
While the biodiesel and ethanol are mainly planned to be focused in the transportation sector, government is focusing mainly on biogas and biomass based producer gas for the energisation of rural poor. Apart from providing much relief from power shortages power projects based on biomass would also open up new avenues for employment generation in rural areas in collection, storage and handling of biomass materials. Each 5MW biomass power project could generate at least 100000man days per year of employment in rural areas (1). In the view of the great potential of biomass based power generation, the Ministry of Non conventional Energy Sources (MNES), has launched comprehensive programmes promoting all three possible routes for conversion of biomass into electricity namely, combustion, cogeneration and gasification.

Rural Energy Programmes (IREP) being implemented by MNES aims at meeting the energy needs of the rural poor, where biofuels have a significant role. The objective of the programme is to provide energy services for multiple applications of the rural society through non-electrical renewable means. Programme has been expanded to 263 districts during this year and energy plans for over 100 clusters of villages and districts have already been prepared and are being finalized (12, 13). Another important initiative from the MNES is the Village Energy Security Program (VESP). Availability of technologies and resources in place for the conversion of biomass into different forms of energy in a cost effective and efficient manner, provide opportunity for rural community to free from energy insecurity. Keeping this point in view an energy plan is already formulated by MNES for a typical village of 100 households with management by the local community along with an indicative financing structure. The plan aims towards providing energy security in villages by meeting total energy needs for cooking, electricity and motive power through various form of biomass material based on available biomass conversion technologies and other renewable energy technologies, where necessary. Such a programme will extend beyond the concepts of oil security or rural electrification per se as generally understood (12). The task of electrifying remote villages that will not be connected to electric grid is being carried out under Remote Village Electrification Programme (RVEP). Around 25000 villages have been identified to date and the process is continuing. Electrification through biomass gasifiers is one of the main focuses under this programme. Government views biogas technology also as a rural economic engine under the National Biogas Programme. To promote and disseminate information about biogas technologies, specifically the government has organized the National Project on biogas development, which is recently modified as National Biogas and Manure Management Programme (NBMMP) (10, 12).

Thus, government continues to drive the Biofuels program in India in a fast pace. Some of the most important biofuels behind the growth of Biofuels program in India have been elaborated in the coming sections.

2. Biodiesel
Biodiesel is mainly produced from oil crops such as rapeseed, sunflower, waste cooking oils, and animal fats. The extracted oils are converted by transesterification
to produce biodiesel. Biodiesel is used in compression-ignition diesel engines usually as a blend in captive fleets such as city buses and also in its pure forms often in modified engines. Government’s Initiative for the wide spread utilisation of Biodiesel as a domestic and environmental friendly fuel supply made the demand of the fuel to grow exponentially in the coming years. Demand projections of biodiesel in the transportation sector is summarised in the following figure.

![Demand of Biodiesel in transportation sector of the country](image)

Fig.2 Demand of Biodiesel in transportation sector of the country

### 2.1 Prospective Feedstocks for Biodiesel

For the reason of edible oil demand being higher than its domestic production, there is no possibility of diverting this oil for the production of biodiesel. Fortunately there is large portion of degraded forestland and unutilised public land field boundaries and fallow lands of farmers where non-edible oil seeds can be grown. Further, country has large arable land as well as good climatic conditions with adequate rainfall in the large part of the area to account for large biomass production each year.

There are many non-edible species, which bear seeds rich in oil. Some plants and seeds in India have tremendous medicinal value, considering these plants for biodiesel production may not be a viable and wise option. Of these some promising tree species have been evaluated and it has been found that there are a number of them such as *Jatropha Curcas* and *Pongamia pinnatta*, which would be very suitable in our conditions. *Jatropha curcas* has been found most suitable for the purpose. It can grow in degraded lands located in poverty stricken areas and in degraded forests. It will also be planted in public lands such as along the railways; roads and irrigation canals. One hectare Jatropha plantation with 4400 plants per hectare under rain fed conditions can yield about 1500 litres of oil. It is estimated that about 3 million hectares plantation is required to produce oil for 10% replacement of petrodiesel.
The residue oil cake after extraction of oil from Jatropha can be used as organic fertilizers. It is also estimated that one acre of Jatropha plantation could produce oil sufficient to meet the energy requirement of a family of 5 members and the oil cake left out when used as fertilizer could cater to one acre. The fact that Jatropha can be grown in any wastelands with less irrigation gives it a distinct advantage for consideration as the prime biodiesel feedstock in Indian conditions.

2.2 Utilization of Wastelands for Biodiesel Energy Plantations
The Detailed Project Report (DPR) undertaken by TERI estimates six categories of wasteland spread over approximately 41.93 Million ha of land spread out in 29 states and union territories as the potential areas for jatropha plantation (19). These include gullied and ravened land and upland with or without scrub, shifting cultivation area degraded land under plantation crop and degraded pastures / grazing land and under utilized degraded notified forestland. According to the climatic conditions, 26 states have been selected and all these states have 40 million ha of potential area where jatropha can be planted as identified in the Detailed Project Report (DPR) prepared by TERI for three macro missions for raising jatropha plantations. In the first micro mission initiated by the Ministry of rural development, two categories of wasteland have been selected that is gullied and or ravenable land and upland with or with out scrub. In the second micro mission by the ministry of agriculture three categories of waste lands have been considered, that is shifting cultivation area, degraded land under plantation crops, and degraded pastures/-grazing land. In the third micro mission by the department of forest, one category under utilized degraded notified forestland has been considered.

2.3 Technological Aspects
Since research on Biodiesel is its infant stage in India, there is an urgent need to revamp research relating to technology for its production and application, mechanisms for efficient utilization of byproducts, evaluation studies in engines with respect to emissions, additive response etc. Improved technologies would result in higher yield and better quality of biodiesel. Concerted R & D effort is needed to produce high quality feedstock material and develop improved cost effective and efficient Biodiesel production systems. It is desirable to carry out tests on Biodiesel from all possible feedstock available in India and also on methyl and ethyl ester based on same feedstock to generate comparative data on fuel compositions, lubricity, oxidation stability, emissions and materials compatibility etc (16). Toxicological study should be initiated in India through concerned R & D centers, as it is a pre-requisite for the introduction of any fuel.

Research efforts for perfecting an efficient chemical or catalyst conversion process are ongoing and need to be pursued further (2). Because of the different problems faced by the homogeneous catalyst, new tools have to be applied using heterogeneous catalysts. Further, lipase catalyzed transesterification process deserves priority attention as its more environmental friendly and convenient to use. This aspect needs to be promoted with priority. This includes study on identifying the appropriate lipase, purification of enzyme through modern efficient techniques like expanded bed chromatography, affinity precipitation and three phase partitioning. The emerging alternative technologies such as the application of smart polymers have to be seriously looked into (2, 16, 19).
2.4 Policy Options
Though Biodiesel can only supplement the diesel in the long run, in the present scenario the implementation of biofuel for blending needs some policy oriented support from the government. It can come through tax exemptions, excise duty and custom duty exemptions. The sales tax on diesel at present rate is 12%, which is proposed to be taken to 20%. Biodiesel being novel to the market, require some exceptions as far as the sales tax, excise duty, and customs duty is considered. The exemptions on biodiesel ought to be made keeping in view of various duties being imposed on diesel.

3. Ethanol
Bioethanol is mainly produced from fermentation of sugar containing materials such as molasses, sugar cane, serial crops, sugar beet and sweet sorghum. It can be blended with conventional petrol usually as a 5% additive and can be used in modern spark ignition engines with out modifications.

3.1 Demand-Supply Scenario
Present installed capacity of alcohol production in the country is 2900 million litres (16). With the present availability of molasses (10 MMT), alcohol production is 2475 Million litres out of which around 628 Million litres is surplus after meeting the demand of industrial use (607 million litres) and potable use (728 Million litres). With 5% blending ethanol requirement for the year of 2005 - 06 is 596.9 Million litres which if not exported, is just sufficient to meet the present ethanol demand in India. Projections of ethanol requirement in gasoline blending in the next coming years is given in the figure (3).

But when we consider 2010 – 11 scenarios for accomplishing the minimum-blending requirement of 10%, 1629 Million litres of ethanol is needed. Along with the gasohol program, planning commission’s exhaustive plan for National Mission on Biodiesel will also lead to a huge requirement of alcohol in the country. Generally alcohol requirement is a minimum of 10% by weight of Biodiesel. Dependence of methanol
for this requirement is severely constrained from the heavily import of this petroleum derivative. Further more, high-level fluctuation in the price of methanol is another major apprehension. Use of ethanol must be encouraged in the sector as it is based on renewable resources. Ethanol demand projection in the biodiesel sector is given in the figure (4).

In short from the above figure, by 2011-12 country needs 3325 Million liters of ethanol only for transportation sector apart from the demand from both industrial and potable applications. But to meet the demand of the ethanol in 2011-12, use of molasses as a resource will not sufficient enough to provide 5% ethanol gasoline blending as mentioned in the gasohol Programme. Therefore to meet the huge demand at parity price of imported petrol and diesel it would be necessary to use a variety of substrates for ethanol production in India. Details of available alternative feedstocks and analysis of different scenario of ethanol production from these feedstocks are summarized in the following sections.

3.2 Alternate Feedstocks: Availability Vs Accessibility
Indeed, the maximum potential of ethanol production from molasses is estimated to be about 2.5 billion litres only. On the other hand, option of food crops (starch based feed stocks) as feedstock is constrained from the point of view of food security and economic implications. Additional resources for ethanol production are essential for the time being. Different resources that can be utilised for ethanol production and their comparative evaluation is summarised in the following sections.

3.2.1 Direct Sugar Utilization for Ethanol Production
As government is already actively involved in formulating the policies, which mandate ethanol blending in the country, it is the high time for the sugar industry to take it as an opportunity to diversify its factories as sugar-ethanol-co product complexes. About 50% of the sugar could be used for export quality white sugar production and the rest for ethanol production. In a sugar factory attached with a distillery, if the sugar price is low, more sugars can be diverted to ethanol production in the form of cane juice or cane syrup. In the off-season molasses can be used for ethanol production. Option of using secondary juice as an ethanol resource also can be looked into. The trials on large-scale ethanol production has already been carried out at 2500 TCD factory partly from secondary cane juice and rest from molasses in 2003 Based on this experience it is estimated that a 30 KLD distillery using cane juice for 120 days and cane molasses for 180 days in an year will earn a net profit of Rs. 302.52 lakhs per annum (15). It has also been projected that such a proposition will lead to additional benefits like stable sugar prices, export quality sugar production, adequate availability of ethanol, higher potential for export power and remunerative prices for sugar cane. Considering the surplus sugar production in the country it will provide an outlet for the cane production if some sugar is diverted to ethanol production. A part of juice can be directly converted to ethanol thus saving energy and achieving higher yield and reduction in spent wash (15).

3.2.2 Sweet Sorghum for Ethanol Production
Sweet sorghum is one attractive feedstock for ethanol production because of the its advantages of the plant with year round cultivation and tolerant capability to drought, acidity, alkalinity and salinity. Therefore cultivation is possible is most parts of India during monsoon, summer and also during winter in south. Due to
short cycle of 3.5 – 4 months, usually up to two cycles are possible on same land yearly in certain irrigated regions. In addition, harvesting and cultivation practices are simple and similar to sugar cane. Also it requires less water and fertilizer compared to sugarcane and is resistant to water shortage conditions. It also gives bagasse as the co product, which is a source of energy for distillery operation. The crop can provide a cane yield of 35 – 40 tones/ha and 65% juice recovery is possible under factory conditions. Grain yield is about 1.5 – 2.5 tones /ha. Further more than two cycles in a year will yield high amount of sugar and ethanol. It has been estimated that sweet sorghum based ethanol is cheaper compared to molasses based ethanol (5, 18).

One of the major factors, which support sweet sorghum, as a feedstock in India is the possibility of cultivation and processing for ethanol during non-crushing season (18). In the regions where favorable climatic conditions allow sweet sorghum cultivation and harvesting for more than 7 – 8 months standalone distilleries can use sweet sorghum as major feedstock. Standalone distilleries need to install pre-processing machinery specially designed to extract juice from sweet sorghum for its clarification/evaporation. There is a possibility to generate excess electricity for commercial sale. These factors could reduce production cost of ethanol.

3.2.3 Sugar Beet
At present, two thirds of world sugar production is obtained from sugar cane and one third from sugar beet. These two crops are in competition, but complementary since they are cultivated for specific requirements in two different climatic belts. In European countries sugar beet is preferred. Though a new crop, sugar beet is having certain advantages over sugarcane such as lower cycle of crop production, higher yield, and high tolerance of a wide range of climatic variations, low water and fertilizer requirements etc.

3.2.4 Cellulose Based Ethanol: An Unexploited Future Resource
The most significant and cheapest feedstocks which we usually ignore, but deserve priority attention is cellulose based ethanol production. We have abundant availability of cellulose residues in the country which come around 800 Million tonnes, which are not used to derive the desired economic potential. If 10% of this potential can be exploited, around 15 billion litres of ethanol can be produced with 60% conversion efficiency (assuming that all agro residues contains an average of 50% cellulose and hemicellulose sugars). But logistics of raw material availability (collection, storage and handling) to meet large future demand is a major issue. For example rice straw based ethanol production would require the location of the plant within a reasonable distance from the rice farms. Moreover the seasonable availability of the feedstock would need either large storage facilities or would need plants to operate on multiple feedstocks for their continued operation through out the year. In India ethanol plants are comparatively very small in capacity. This brings other related issues such as feed stock availability, scale of operation, large investment for installation etc. keeping in view of the logistics of feedstock procurement, a decision is needed whether it is advisable to build very large plants as increased contribution towards cost in terms of collection and transport of large amount of feedstock may offset savings due to economies of scale (17).
Keeping these points in view, among all other agro residues, bagasse is found to be the best feedstock since it is centred on sugar factories. The sugar cane Bagasse and sugar cane trash can be used partly for co-generation and partly for ethanol production. National Renewable Energy Laboratory conducted a detailed study on the feasibility of bagasse based ethanol production in Maharashtra. It has been observed that excess bagasse produced from three sugar mills in Maharashtra can satisfy the whole requirement of ethanol in Mumbai assuming that all gasoline in Mumbai is sold as an E10 fuel (90% petrol and 10% ethanol) (11). This holds considerable promise for the future and rays of hopes for cellulose based ethanol sector in India.

But one should agree the fact that research on bioethanol in India is its infant stage. While in US, because of the continuous efforts for the last 20 years they were able to produce ethanol at a competent price of 39.5 cents per litre (14). According to the NREL projections in another 15 years time ethanol production cost of 20 cents per litre will be possible by employing cellulose rich and lignin lean feedstock, a highly efficient cellulase producer and SSCF (Simultaneous Saccharification and Fermentation) process improvement (17). These cost projections indicate that improved conversion technology is the largest contributor to reducing the cost of production. These cost projections are definitely useful indicators to decide our research priorities for ethanol production from lignocellulosic biomass.

3.3 Technological Hurdles in Indian Ethanol Sector and Priority Research Needs
Fermentation technology for fuel ethanol production has been commercially established. But for the simultaneous utilisation of different resources apart from molasses, fermentation and distillation technologies need to be imported from abroad. Molecular sieve dehydration technology has been found to be more economical environmental friendly and superior grade ethanol producing than conventional azeotropic distillation processes. Some developments recently have seen in the aspects of development of a viable process and technology having low wastewater discharge and low fresh water demand and energy needs (15). The technologies are claimed to provide high ethanol yields due to special process ensuring good viability, which does hold great promise in the Indian ethanol sector.

Technological barriers are more severe for lignocellulose based ethanol production. The lack of an effective pre-treatment process for decrystallizing cellulose, allowing rapid enzyme accessibility and efficient enzymes for conversion of pre-treated substrates to fermentable sugars are the main two issues. Majority of the present pre-treatment processes is chemically catalysed, but both economic and environmental arguments drive the development of physical pre-treatment. Enzymatic processes under development are supposed to have roughly equal or even decreasing costs today, and are environmentally sounder (17). But it is time consuming. Therefore what is needed is an integrated process, which combines both chemical and microbial treatments with out the formation of fermentation inhibitors and yield maximum ethanol within reasonable time. Though a lot of small activities have been happening in India in various aspects of chemical, mechanical and enzymatic hydrolysis, there were no coordinated and integrated research efforts on this aspect. Various research activities from the multi disciplinary angles started by The Energy
and Resources Institute (TERI), New Delhi towards this direction is giving both hopes and aspirations for further improvements in the technology.

3.4 Policy Issues
Fuel ethanol production undeniably needs a proper policy orientation, which will ensure success of the whole ethanol programme in India. The future of gasohol programme depends on parity of ethanol pricing with that petrol on ex refinery basis. The petrol prices vary with the price of crude oil while ethanol price vary with that of molasses and cane. Moreover, interest burden on tender money deposit with companies and one month delayed payments of ethanol supply are another related issues. There is no fixed reasonable negotiated price of ethanol valid for three to four years. Complicated procurement system that affects the regular supply of ethanol to the oil depots has to be overcome. One should also agree that there is a delay in procurement, import and export permits for ethanol by state excise authorities. There is a need to evolve a system for proper unloading of ethanol tankers at oil depots with out delay on the part of excise authorities. Variable tax and duty structures on ethanol from state to state is also a concern. A uniform policy for prevailing taxes and duties on molasses and alcohol is the need of the hour. Further, there is no adequate relief on excise duty surcharge on ethanol-doped petrol as against petrol. Import/export duty permits and other levies on inter state movement of alcohol should be removed (15).

The time truly calls for a National Mission on Bioethanol as well. For transforming the vision of ethanol driven energy sector in India to reality, it is essential to formulate a road map for achieving the goals. Therefore, an analysis of the existing challenges in the bioethanol sector in India, strengths, infrastructure required and the gaps are essential. This will enable bioethanol to be a major energy source in our country by 2015. In order to accomplish this it may also be necessary to share lessons and technology from the other international and national stakeholders and their experience on biofuels development.

4. Biomass Power/ Cogeneration and Gasification
Biomass for power generation has been recognized as an important component of the renewable energy programme in India and this is reflected in the priority attached to it by the MNES. There are niches with substantial potential for the use of biomass for power generation e.g. bagasse cogeneration in sugar mills, decentralized gasifier-based diesel cogeneration systems in south India, and biomass waste from agricultural operations or agro-industries in concentrated geographical pockets. A biomass power / cogeneration capacity addition of 115 MW in six states was created in the country during the year reaching a cumulative power generation capacity of 727 MW. State of art biomass power/cogeneration projects designed with boiler configurations of 87 bar and high pressures are now being installed in the country. Optimum cogeneration capacity installed in Indian Sugar Mills is perhaps one of the highest among all the sugar producing countries in the world (12).

The biomass-based cogeneration in the country is being encouraged through beneficial policies at the central and state levels. A number of policy initiatives have been introduced for encouragement to commercial exploitation of biomass power potential since 1993. Incentives include sales tax and excise duty exceptions reduced customs duty, accelerated depreciation etc. electricity regulatory commission set up
different states have also noted the relevance of these technologies and hence announced policies for purchase/wheeling/banking of power generated from biomass power/cogeneration projects. The ministry has identified favourable policy guidelines, which generally lead to faster promotion of optimum bagasse based co-generation projects in the Indian Sugar mills. These include a fair and attractive purchase price for the generated electricity, prompt payments for the purchased electricity, honouring of signed PPAs, expeditious statutory permissions wherever required, long term stability of required policies (12).

With easy availability of biomass residues in India, there exists a tremendous potential for biomass based gasifier based systems, both for power generation as well as for thermal applications. The potential for biomass utilization in general and biomass gasification in particular indicates that, even taking into account the demand for fodder etc., the biomass available in the country (excluding animal residues) can optimistically support electrical power plants aggregating to a total of 17,000 MW. For using wood 1 MW can be generated from a 3-hectare energy plantation. Due to accelerated activities in agricultural sectors and agro processing industries the explorable potential is as high as 50,000 MW. The sugar industry alone is capable of producing over 3,000 MW of surplus power through bagasse-based co-generation systems. Biomass gasification programme is also governed by the MNES (Ministry of Non conventional Energy Sources). In cognisance of the vast potential of biomass gasification technology for meeting mechanical, electrical, and thermal energy requirements in various sectors of the Indian economy, MNES launched an ambitious research, development, and demonstration programme on biomass gasifiers in early 1986. So far, there are more than 1700 gasifier systems installed in the field throughout the country with a cumulative installed capacity of more than 35 MW (20).

The programme provides financial support to manufacturers and users of biomass gasifiers in India. In order to address issues relating to technology, performance, life of gasifier, and other related aspects, and to promote commercialisation of gasifier systems, MNES aims at encouraging manufacturers of gasifiers. The Ministry provides funds for the cost sharing of the gasifier systems (subsidy) to state nodal agencies and this in turn is distributed to the manufacturers. Higher subsidy up to 90% is given in high-thrust areas like hilly regions and the northeastern states. The nodal agencies are expected to assist in subsidy distribution, and monitoring the performance, and seeking support from the manufacturers so that the users can obtain the expected benefits.

There are several other imperative issues, which need to be addressed such as such as management of biomass supply in tribal villages for biomass based power generation, a better understanding of the livelihood issues and demonstration of increased livelihood options, issues related to ownership and management model, shortcoming of Wood based gasifier system for power generation as a complete technology package, capacity building issues for different actors etc.

5. Biogas
In India biogas has been in use since 1960s. But is only in 1981, with the beginning of the sixth five year plan, the formulation of the national project for biogas development has taken an appropriate shape (10).
Currently there are thought to be about 3.67 million biogas plants installed around the country till the end of 2003-04. In the mean time country has an estimated biogas potential of 17000MW considering only the agricultural residues and dung from our 300 Million cattle (10). Apart from these feedstocks, the plant can be maintained by other variety of organic residues. While the gas is an excellent substitute for conventional fuels such as diesel, petrol and electricity, process provides biomanure having superior nutrient quality. While treating organic wastes, it stands as a cleaner of our surrounding preventing the pollution problems and spread of pathogens. Further more, the gas can also be used to power engines in a dual fuel mix with petrol and diesel and can aid in pumped irrigation systems. Apart from these direct benefits, tangible benefits are there such as elimination of drudgery to rural women minimizing the task of fuel wood gathering, positive environmental performance by minimizing the emissions etc. In short, biogas systems thus offer an integrated system that lends itself to a rural setting.

In the dissemination programme, there is a wide variation in performance level between different regions in India. A 40-70% acceptance have been noticed among the disseminated plants in India (3). There are both technical and policy related issues behind the low dissemination and poor performance of biogas plants. There are cases where there is unsatisfactory technology, inadequate maintenance and repair, lack of resource availability etc. off course, a target driven dissemination leading to plants built incorrectly for poorly motivated families is another major concern. Still there are instances of very high-level success in dissemination and success of biogas plants. Bhat et al has conducted a study to understand these success factors in some selected areas of the country so that this model can provide lessons to promote biogas programmes in other regions as well. Realization among rural house holds about the need for a high quality fuel, efficient collection and use of cattle dung resource, a high stake for quality biomanure, entrepreneurs’ dependence on biogas plant construction for their livelihood, a well functioning dissemination network involving multiple agencies with sufficient stake, adequate and quality follow up services are found to be the key factors behind the success.

The programme is being implemented through state nodal departments and agencies and Khadi and Village Industries Commission (KVIC) besides a few government organizations. The programme is being implemented with a village cluster approach to make the necessary effectivity in the programme, the action taken include preparation of micro plans, demarcation of area of operation for each agency, sharing of list of beneficiaries among different agencies, maintaining database of village base beneficiaries, embossing identification marks on each plant and fixing of photographs of beneficiaries in subsidy disbursement records (12).

The ministry provides Central Financial Assistance for construction and maintenance of biogas plants, training and awareness creation, technical centers and service charges or salary support to implementing agencies. Besides, the Reserve Bank of India (RBI) and the National Bank for Agriculture and Rural Development (NABARD) have been supporting the biogas programme in India. Also Biogas development and training centers have been established by the ministry at various locations of the country for providing technical support, carrying out R & D conducting training programmes and thereby creating awareness. The Ministry has been supporting R & D projects in the area of biogas for process improvement and
enhanced methane production through microbiological, biochemical and engineering techniques. It is undertaken though universities, national laboratories, research institutions (12).

There is still enormous potential for biogas technology and the government continues its drive for more wide spread implementation. Biogas has been shown to be a useful component in the rural economy in India though its applications are logistically difficult. Coordinated dissemination has led to high rates of non-functioning plants and may endanger further uptake. Besides its status as a fuel remains marginal. Participation in biogas technology varies across socio economic groups and across regions. Despite a well-intentioned attempt to cater the free energy needs of rural India and particularly the poor, the biogas programmes has not appeared to meet the needs on any meaningful scale. Limited success occurred in other agricultural groups also. The very current situation regarding the status of biogas technology in India is unknown though the dissemination is still being undertaken. The vision of large-scale implementation of biogas programmes making our rural economy self-reliable in terms of energy is still remains unrealized though small steps may have been achieved.

6. Conclusions
The prospect of massive fuel import bills and the environmental pollution due to the recent economic growth and the prospects of further growth in the coming decades, adds to the pressure to make sure that biofuel programs are implemented in the earnest way. Though initial investment cost may be higher for biofuel technologies, feedstock diversity and multi-feedstock production technologies will play a critical role in reductions in production cost and making the fuel economically viable. In order to support this nascent industry the government needs to encourage pilot projects and R&D work on biofuels to establish techno-economic viability of large-scale production. The process and production stage for biofuel may become very decentralized and uncontrolled down the line. In addition, there is an urgent need to frame appropriate legal and policy framework on bio-fuels. This will provide much needed clarity to the entire sector.

Development of a self-reliant community to manage the natural system is one of the important elements of sustainable development. Here lays the importance of biofuels as a domestic and renewable energy supply. While bioethanol and biodiesel can be foreseen as future fuels in the transport sector, biogas and biomass technologies are truly workable in rural India. But commercialization of these fuels on a large scale needs tremendous technological innovation supported by proper policy approaches. Government of India is very keen to give it a head start for all the biofuels programs. A concerted effort from both the government and private parties towards a coherent technological and policy initiative will lead India to meet its energy requirements substantially through biofuels materializing the vision ‘Swadeshi’ of Mahatma Gandhi, thereby creating a revolutionary changes in our nation’s development.

Reference


Green Power Markets Development in Southeast Asia: Electricity Industry Reforms and Policy Convergence

Romeo Pacudan, PhD
UNEP Risoe Centre, Risoe National Laboratory
Roskilde, Denmark

Abstract

The green power markets in Malaysia, the Philippines and Thailand have gradually emerged as a result of the introduction of electricity industry reforms that allow private participation in power generation though market access programmes and the provision of various incentives to green power private investments. Despite the diversity in resource endowments, national energy policies, and power industry reform paths and structures, it appears that renewable energy frameworks are converging. These countries elaborated national energy strategies and defined renewable energy targets. Grid access programmes were launched while new policy instruments such as renewable energy portfolio standards (RPS) are introduced or being planned for near future implementation.

Keywords: Green power markets, renewable energy; renewable energy policy and regulatory frameworks; Southeast Asia
1. Introduction

Malaysia, the Philippines and Thailand are endowed with abundant renewable energy resources, though their rate of utilization is relatively small compared with conventional fuels. These countries are pursuing to develop their renewable energy resources with various objectives such as energy security enhancement, environmental protection, energy access improvement and investment promotion. With power sector reforms at the backdrop, each country developed various green power frameworks to encourage private sector investments on grid-based renewable energies. Renewable energy strategies, targets, policy instruments, grid access programmes and financial incentives were being elaborated, defined and implemented by these countries. The paper reviews and compares various elements of green power markets in these countries.

2. Diversity in Energy Resource Endowments

The Southeast Asian region consists of countries with diverse energy resource endowments (Table 1). Among the three countries analysed in this study, Malaysia is at present the only net energy exporting country. Both the Philippines and Thailand are highly dependent on imported energy to fuel their economic development. Natural gas, hydropower and biomass energy resources in Malaysia are significant. Thailand has huge brown coal reserves though natural gas and biomass energy resources are also important. In the Philippines, energy resources with substantial potential are renewable energies, wind and geothermal, though gas and coal resources are also substantial.

<table>
<thead>
<tr>
<th>Table 1: Energy resource potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malaysia</td>
</tr>
<tr>
<td>Oil reserve (billion barrels)</td>
</tr>
<tr>
<td>Gas estimate reserve (billion cubic meters)</td>
</tr>
<tr>
<td>Coal proven reserve (million tons)</td>
</tr>
<tr>
<td>Hydropower technically feasible (TWh/y)</td>
</tr>
<tr>
<td>Geothermal potential (MW)</td>
</tr>
<tr>
<td>Wind energy potential (MW)</td>
</tr>
<tr>
<td>Biomass (MW)</td>
</tr>
<tr>
<td>Thailand</td>
</tr>
<tr>
<td>Oil reserve (billion barrels)</td>
</tr>
<tr>
<td>Gas estimate reserve (billion cubic meters)</td>
</tr>
<tr>
<td>Coal proven reserve (million tons)</td>
</tr>
<tr>
<td>Hydropower technically feasible (TWh/y)</td>
</tr>
<tr>
<td>Geothermal potential (MW)</td>
</tr>
<tr>
<td>Wind energy potential (MW)</td>
</tr>
<tr>
<td>Biomass (MW)</td>
</tr>
<tr>
<td>Philippines</td>
</tr>
<tr>
<td>Oil reserve (billion barrels)</td>
</tr>
<tr>
<td>Gas estimate reserve (billion cubic meters)</td>
</tr>
<tr>
<td>Coal proven reserve (million tons)</td>
</tr>
<tr>
<td>Hydropower technically feasible (TWh/y)</td>
</tr>
<tr>
<td>Geothermal potential (MW)</td>
</tr>
<tr>
<td>Wind energy potential (MW)</td>
</tr>
<tr>
<td>Biomass (MW)</td>
</tr>
</tbody>
</table>

Sources: ASEAN (2003)

Table 2: Electricity generation mix

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>4,444</td>
<td>7,869</td>
</tr>
<tr>
<td>Thermal (coal)</td>
<td>8,953</td>
<td>14,517</td>
</tr>
<tr>
<td>CC/natural gas</td>
<td>21,636</td>
<td>13,139</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>1,141</td>
<td>2</td>
</tr>
<tr>
<td>Diesel/oil-based</td>
<td>3,573</td>
<td>7,514</td>
</tr>
<tr>
<td>Geothermal</td>
<td>9,822</td>
<td>1</td>
</tr>
<tr>
<td>Non-conventional</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SPP</td>
<td>50,173</td>
<td>10.9%</td>
</tr>
<tr>
<td>Energy Purchased</td>
<td>3,378</td>
<td>2.6%</td>
</tr>
<tr>
<td>IPP</td>
<td>50,173</td>
<td>39.2%</td>
</tr>
<tr>
<td>Total</td>
<td>38,606</td>
<td>100%</td>
</tr>
</tbody>
</table>


Despite the abundance of renewable energy resources in these countries, its current utilization for power generation is relatively low compared with conventional fuels. (In these countries, large hydro are considered part of conventional energy resources) (Table 2). More than 50 percent of Malaysia’s electricity generation are from natural gas, followed by coal at around 20%, while hydro and diesel have almost similar shares at around 10%. In Thailand, natural gas accounts for more than half of electricity generation (IPPs mostly natural gas) followed by coal. Natural gas,
coal and diesel fuel contributes around two-thirds of electricity generation while hydro and geothermal combined, constitute around one-third of electricity generation.

3. Diversity in Energy Policies

While the three countries have common energy policy objectives of energy security enhancement, environmental protection and investment promotion, different policies were pursued in the overall energy development. Malaysia is seeking to achieve an optimal and balanced development of its energy resources. Thailand aims to develop its energy resources but is giving emphasis on energy conservation and its strategic geographic location to become a regional energy centre. The Philippines being the least endowed with energy resources, seeks to develop all available resources to achieve greater energy independence.

As presented earlier, Malaysia is a net energy exporting country. But with its robust economic growth since the past decades, it is projected that the country will become net energy importing in the medium term. The government considers three key objectives that are instrumental in steering the development of the energy sector: supply objective – to ensure the provision of adequate, secure, and cost-effective energy supplies; utilization objective – to promote efficient utilization of energy; and environmental objective – to minimize the negative impacts of energy to the environment. Two core policies being pursued by Malaysia since the 1980s are the national depletion policy and fuel diversification policy. The national depletion policy was initiated in 1980 to safeguard the oil and gas resources by limiting the oil and gas production. The fuel diversification policy was launched in 1981 with the objective of reducing overdependence on single fuel. Four main fuels were initially considered in the policy: oil, hydro, gas and coal (also known as the four-fuel diversification policy). In 2000, the government incorporated renewable energies as the fifth fuel in what is known as the five-fuel diversification policy.

Similarly in Thailand, there is an overall recognition of the important role played by energy in the country’s economic development and competitiveness. The current government seeks to conserve, develop and promote the efficient utilization of energy while balancing the development of indigenous natural resources and the protection of the environment with the ultimate goal of reducing reliance on energy imports. Four main strategies were developed to support the country’s economic development and regional integration: i) strategy for efficient use of energy – reducing energy intensity from 1.4:1 to 1:1; ii) strategy for energy security – ensure sufficient and reliable energy supply for at least 30 years; iii) strategy as a regional energy center – develop land bridge and energy hub; and iv) strategy for renewable energy development – increase the share of renewable energy in the final energy consumption from 0.5% at present to 8% in 2011.

The Philippine energy sector agenda is framed against the backdrop of the government’s national development agenda, which seeks to support macro economic stability; job creation, social development, decentralized development, and good governance and national harmony. The government defines two main energy sector agenda: i) energy independence, and ii) power market reforms. Among the three countries analysed in this paper, the Philippines is the least endowed with energy resources. The energy independence agenda has an overall target of increasing energy self-sufficiency to 60% in 2010. This would be achieved by increasing oil and gas reserves, developing renewable energy potential, increasing the use of alternative fuels, forging partnerships with other countries, and strengthening energy efficiency and conservation. The overall goal of power market reforms agenda is to generate fair and reasonable energy prices in a competitive environment. This would be attained by creating a transparent power sector privatisation process and establishing an investment climate attractive to investors.

4. Diversity in Electricity Reform Paths and Structure

The three countries have introduced reforms in their electricity supply industries since the 1980s. One of the main reform goals is to take advantage of the private capital in meeting supply capacity expansion.
Among the three countries, only the Philippines currently pursues privatization and restructuring of the electricity supply industry. It is also aiming to lower electricity prices with power industry reforms. Prior to these reforms, the generation and transmission functions were mainly vested on the National Power Corporation, a wholly-owned government corporation. The electricity distribution was carried out by private utilities in major cities and electric cooperatives in rural areas. Reforms started in 1987 with the issuance of Executive Order (EO 215) which facilitated the entry of independent power producers into the wholesale electricity market. In 2001, the government passed into law Republic Act No. 9136 also known as the Electric Power Industry Restructuring Act (EPIRA). The act embodies restructuring of the electricity supply industry separating the generation, transmission, distribution and supply functions; introduction of competition in the wholesale and retail electricity markets; and privatization of the state-owned generation and transmission company, the Philippine National Power Corporation (NPC) through asset divestiture. These reforms were aimed at encouraging greater competition and at attracting more private-sector investments in the power industry. A more competitive power industry is also envisaged to result in lower power rates and a more efficient delivery of electricity supply to end-users.

Currently the Philippine electricity supply industry is in transition. The integrated assets of NPC were broken down and its generating assets were prepared for privatization by the Power Sector Assets and Liabilities Management Corporation (PSALM). The National Transmission Company (TRANSCO) was created to carry out high voltage transmission and sub-transmission functions, and will be privatized through concession. To prepare for the operations of the wholesale electricity spot market (WESM), the Philippine Electricity Market Corporation (PEMCO) was established in 2003. The Energy Regulatory Commission (ERC) was created to be responsible for economic regulation. Rural electrification will be initially supervised by the National Electrification Administration (NEA) and missionary electrification by the Small Power Utilities Group (SPUG) of NPC. The operation of the competitive wholesale electricity market is programmed in 2006 while retail competition in 2007.

In Peninsular Malaysia, the generation, transmission and distribution were vertically integrated under the National Electricity Board (NEB). The high economic growth in the 1980s resulted in acute power shortages in the 1990s. This prompted the government to pass the Electricity Supply Act in 1990. The government introduced reforms with the belief that the power industry will be best driven by free market principles and which will lead to more investment to meet the challenge of rapid demand growth. In 1990, NEB was corporatized to become the wholly-owned government company, Tenaga Nasional Berhad (TNB), with regulatory oversight from the Department of Electricity and Gas Supply (JBEG). TNB was privatized in 1992 allowing the private sector to own 30% of the company. The government allowed entry of independent power producers (IPPs) in 1994 with contracts directly negotiated with TNB. TNB Generation Sdn Berhad was created to take over all the generating assets of TNB and was required to sell power to TNB through power purchase agreement similar to IPPs. The Energy Commission (EC) was created in 2000 to be responsible for the economic regulation of the power industry. There were plans from the government to move forward with reforms and introduce wholesale competition. The failure of the California Power Pool (US experience), however, influenced the Malaysian government and the power utilities not to further engage in industry restructuring. There was also a realization that private sector alone cannot ensure reliable supply and stable energy prices especially during extreme conditions. At present, electricity generation in Peninsular Malaysia is carried out by TNB Generation Sdn Berhad and IPPs. Transmission, distribution and supply functions are also undertaken by TNB subsidiaries: TNB Transmission Sdn Berhad and TNB Distribution Sdn Berhad.

The electricity supply industry structure in Thailand prior to reforms was characterized as vertically integrated in generation and transmission with the Electricity Generating Authority of Thailand (EGAT) as the main organization implementing these functions. The Metropolitan Electricity Administration (MEA) and the Provincial Electricity Administration (PEA) were responsible for electricity distribution and supply in Bangkok Metropolitan Area and the rest of the country, respectively. There were various attempts to privatize the state enterprises in the
1980s but the major change came in 1992 when the government passed an amendment to the EGAT Act allowing the private sector to engage in power generation. The main argument for introducing reforms was to relieve the government’s financial burden in meeting supply capacity expansion. The Small Power Producers (SPP) Programme was introduced in 1992 while the Independent Power Producers (IPP) Programme was launched in 1994. Since the 1990s until 2001, the government developed a plan to unbundle, privatize and introduce competition in the industry. The Power Pool and Electricity Supply Industry Plan was approved by the government cabinet on 25 July 2000. The change of government in 2001 and the reorganization of energy agencies and the creation of the Ministry of Energy have slowed down the process. The current government is planning to pursue the privatization of state enterprises including the three electric utilities by listing them in the Stock Exchange of Thailand. Thailand’s present electricity supply industry structure is a single buyer model, with IPPs and SPPs having long-term contracts with EGAT, though some IPPs and SPPs are also selling directly to end-users. EGAT remains the dominant electricity generator and controls the national transmission grid. MEA and PEA remain responsible for electricity distribution and supply.

5. Converging Renewable Energy Policy Frameworks

5.1 Renewable energy strategies and targets

Notwithstanding the differences in priorities, resources, goals, and market structures, renewable energy frameworks are converging. These countries have defined renewable energy strategies and targets, and in order to achieve national goals, policy instruments, grid access programmes and financial mechanisms and reinforcing its implementation.

Thailand launched a national strategy, the Strategic Plan for Renewable Energy Development in 2003. The main objective of the country’s renewable energy development is to reduce energy supply burden, reduce energy imports, reduce environmental impacts, and optimize the utilization value of domestic energy resources. Associated with this strategy is the government’s renewable energy target to increase the share of renewable energies in the primary energy consumption from 0.5% in 2002 to 8% in 2011. To achieve the renewable energy targets, Thailand passed the Renewable Portfolio Standards (RPS) in early 1994 setting 4% share of renewable energy capacity for new power plants in 2011. The government is currently devising measures that encourage purchase of power generated by renewable energy such as tax credits, privileges, and subsidies to be supported financially by the Energy Conservation Fund; developing programmes supporting research and development on new renewable energy technologies; encouraging participation and partnerships with local communities in renewable energy-fueled power plants.

Malaysia’s Five Fuel Diversification Policy provides the renewable energy policy guidance. It aims to ensure reliability and security of energy supply, balance energy supply mix and protect the environment. The current grid-based renewable energy programmes embodies national renewable energy strategy. The Small Renewable Energy Power (SREP) programme allows small power generators connection to the grid at selling rates defined by the Renewable Energy Power Purchase Agreement (REPPA). The SREP programme sets a target renewable energy capacity of 500 MW to be integrated into the grid by the end of 2005. To accelerate investments in the palm-oil industry, the government launched the Biomass-Based Power Generation and Cogeneration (BioGen) Programme. Furthermore, the government established a National Steering Committee to identify priorities for research and development of new energy sources from solar, hydrogen and fuel cells.

The Philippines’ Renewable Energy Policy Framework launched in 2003 has an overall goal of reducing the country’s dependence on imported energy, broaden resource base, and save foreign exchange and reduce emissions. The framework sets a target of increasing the renewable power capacity by 100% in 2013 and non-power contribution to energy mix by 100 million barrels of fuel oil equivalent. The government programs aim to achieve this through the existing laws and orders regulating the development of geothermal (Act to Promote the Exploration and
Development of Geothermal Resources, hydro (the Mini-Hydro Law) and wind energy resources (Executive Order 232 encouraging private participation in the development of ocean, solar and wind resource for power generation). To further accelerate the deployment of renewable energies, the government hopes that the Philippine Congress will pass into law the long pending Renewable Energy Bill. The Bill aims for comprehensive renewable energy development and specifies specific measures such as renewable portfolio standard, renewable energy trust fund, fiscal and financial incentives, etc.

5.2 Policy instruments

Among the countries in Southeast Asia, Thailand is the only country so far to have introduced a renewable portfolio standard. The Philippines’ pending Renewable Energy Bill have included renewable portfolio standard as one of the key instruments in increasing the deployment of renewable energies.

Table 3: Policy instruments

<table>
<thead>
<tr>
<th>Country</th>
<th>Policy instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Malaysia</strong></td>
<td>• Pioneer status with tax exemption of 70% of statutory income for a period of 5 years or Investment Tax allowance of 60% in the qualifying capital expenditure incurred within a period of 5 years.</td>
</tr>
<tr>
<td></td>
<td>• Import duty and sales tax exemption on equipment used in the project and are not produced locally. Equipment purchased from local manufacturers is also given sales tax exemption.</td>
</tr>
<tr>
<td><strong>Philippines</strong></td>
<td>• Income tax exemption for 3 to 5 years, or up to 8 years in exceptional cases.</td>
</tr>
<tr>
<td></td>
<td>• Accelerated depreciation of the cost of capital equipment over a ten (10) year period.</td>
</tr>
<tr>
<td></td>
<td>• Special privilege tax rates – Tax payable by developers/grantees to develop potential sites for hydroelectric power and to generate, transmit and sell electric power shall be 2 percent of their gross receipts.</td>
</tr>
<tr>
<td><strong>Geothermal</strong></td>
<td>• Recovery of operating expenses not exceeding 90 percent of the gross value in any year with carry-forward of unrecovered cost.</td>
</tr>
<tr>
<td><strong>Board of Investment Incentives</strong></td>
<td>• Service fee of up to 40 percent of the net proceeds.</td>
</tr>
<tr>
<td><strong>Ocean, Solar and Wind</strong></td>
<td>• Exemption from all taxes except income tax.</td>
</tr>
<tr>
<td><strong>Mini-hydro</strong></td>
<td>• Equipment purchased from local manufacturers is also given sales tax exemption.</td>
</tr>
<tr>
<td><strong>Small Power Producers Subsidy</strong></td>
<td>• Lease or exclusively occupy and use land for the purpose of installing or constructing facilities.</td>
</tr>
</tbody>
</table>

Sources: Author’s compilation

The three countries currently rely mainly on investment incentives and tax measures (supply-capacity category policy instruments). Income tax holidays, equipment duty exemptions, property tax exemption, and accelerated depreciation for the equipment are the common fiscal incentives in
Malaysia, the Philippines, Singapore and Thailand (Table 3). Non-fiscal incentives in the Philippines and Thailand include easy repatriation of capital investments and remittance of earnings as well as permission to bring in foreign experts and their families otherwise prohibited with the current employment regulations. In order to further stimulate private investments on renewables, the Thai government introduced pricing subsidy for the capacity generated by renewable energy on top of the normal power purchase rate from Small Power Producers (SPP) Programme. The program started in 2002, and it projected that at least 300 MW of electricity generated by these renewable SPPs can be exported to the grid by the year 2005.

5.3 Grid-access programmes

One of the earliest stages of power sector reforms in these countries is the opening of the power generation sector to independent power producers (IPPs). The IPP frameworks serve as an important basis for the development of renewable energies. Malaysia and Thailand have moreover developed specific renewable energy IPP frameworks.

With the operation of competitive electricity markets in the Philippines, electricity generators will have direct access to national and distribution grids. The wholesale electricity spot market (WESM) rule also specifies priority dispatch for renewable energy generation. Electricity wholesalers, retailers and contestable customers on the other hand can directly negotiate with generators (including renewable energy) for the bilateral trade of electricity. This however does not guarantee that the wholesale market-clearing price will provide sufficient returns to renewable energy generators. The government at present is studying various options to stimulate private investments on renewable electricity generation under the competitive electricity market setting.

Malaysia recently introduced the Small Renewable Energy Power Programme (SREP) whose aim is to facilitate the implementation of grid-connected renewable energy resource-based small power plants. Grid-connection of SREP is governed by the Renewable Energy Power Purchase Agreement (REPPA). REPPA’s power purchase price is capped by the government at 4.5 cent US$/kWh.

In Thailand, the Small Power Producers (SPPs) program was introduced since the early 1990s and is designed to promote grid-connected electricity generation from renewable energy and cogeneration. A flexible power purchase agreement has been introduced (firm and non-firm) to respond to the technical limitations of renewable energy technologies. Power purchase price is based on the utility’s avoided costs. In 2002, Thailand introduced a new framework that promotes small-scale renewable electricity generation known as Very Small Renewable Energy Power Producers (VSREPP). A VSREPP is defined as a generator with his own generating unit, whose power generating process utilizes renewable energy sources, agricultural and industrial wastes and residues, or by-product steam, and who sells no more than 1 MW of electrical power directly to a distribution utility. The VSREPP regulations allow for net metering arrangements and streamlined interconnection process and requirements so as to minimize the costs of connecting a VSREPP to the distribution systems. Generators with net generation can generate income by selling electricity to the distribution utilities at the latter’s avoided costs (the wholesale price that the distribution utilities pay to EGAT for bulk electricity). The main targets of the VSREPP Program are pig farms and food processing industries.

5.4 Financial mechanisms

One of the main barriers to private investments on renewable power generation is the lack of financing and financial assistance. Various mechanisms were being developed by these countries such as line of credits, low interest loans, grants, and other financial assistance.

Malaysia’s MESITA Fund is a social obligation fund contributed by power generators. Each utility puts in 1% of their annual audited revenue to the fund and this is being used to assist government projects and studies on rural electrification, energy efficiency and renewable energy. Recently, the government launched the Renewable Energy Business Fund to be used mainly for
financing full-scale biomass energy demonstration projects. The Fund could provide financing of up to 80% of the total project cost. Funding will be sourced from the Bank Teknologi Malaysia, GEF and MESITA Funds with total amount of RM28 million.

The Philippines has two sources of financial support intended for rural electrification projects including renewable energies. The Energy Regulation 1-94 (ER 1-94) mandates power generators to set aside PhP 0.01 per kWh of electricity sales to be used for financing projects that benefit the host communities such as rural electrification, watershed management and livelihood programs. The second source is the Universal Charge, a non by-passable charge sanctioned by Electric Power Industry Reform Act (RA 9136). At present the missionary electrification subsidy and environmental charge are levied to the ratepayers through the universal charge. To provide assistance to project developers, the Development Bank of the Philippines (DBP), has established financing programmes providing low interest loans for new and renewable energy and rural power projects. The programme is funded by various overseas development assistance (ODA) funds and the World Bank. Moreover, the current GEF project ‘Capacity Building to Remove Barriers to Renewable Energy Development’ also established 3 funding portfolios to support projects that promote and apply innovative strategies and delivery mechanisms. These are project preparation fund, loan guarantee fund and micro-finance fund.

Thailand’s Energy Conservation Fund (ENCON Fund) is a fund generated from the levy imposed on domestically sold petroleum products. The Fund mainly provides assistance on energy efficiency projects though part of it is used to support renewable energy development: i) as financial assistance to renewable energy project developers, and ii) as subsidy to small renewable energy power producers. More recently the Energy Conservation Revolving Fund, which is initially designed to provide financial assistance to energy conservation projects, has opened up to renewable energy projects. The Fund, managed by 6 commercial banks (Siam City bank, Bangkok Bank PCL, Industrial Finance Corporation of Thailand, Thai Military bank, Bank Thai and Sri Ayutthaya Bank), provides low interest loans at a fixed rate of 4%. The maximum amount set for lending per project is US$1 million. The government also plans to use the ENCON fund for the financial incentives being developed under the Strategic Plan for Renewable Energy Development.

6. Market Deployment

Private sector investments on renewable energies in many Southeast Asian countries were in a similar manner driven by grid access programmes and various policy measures (Table 4). Among the countries in the region, Thailand has so far attracted significant private investments on renewables. Its Small Power Producers (SPP) programme and Power Purchase Agreements (PPA) coupled with investment incentives and production subsidies generated significant capacity additions. The subsidy programme initially budgeted a subsidy payment for around 300 MW capacity but it generated project proposals with more than 700 MW capacity. Even the country’s Very Small Power Producers (VSPP) programme has attracted interests from various agro-industries with the potential of generating small power capacities. The newly adopted Renewable Portfolio Standard (RPS) supported by various incentives (currently being developed by the government) is expected to create capacity additions in the medium term.

Malaysia’s Small Renewable Energy Producers (SREP) programme has also created strong interest from the private sector, as indicated by the number of proposals approved by the government. However, only 12 MW capacity has been added at the beginning of 2005 which is far below the Programme’s target of 500 MW capacity addition at the end of 2005. The Malaysian government however needs to modify the current Renewable Energy Power Purchase Agreement (REPPA) in order to attract private investments on renewables. Improvements proposed include the following: increase of the power purchase rate from the cap of RM 0.17/kWh to RM0.22/kWh to provide reasonable returns to investors, and standardization of REPPA to include performance flexibility and improved bankability provisions in order to attract investment financing.
The Philippines’ fiscal and non-fiscal incentives for geothermal, mini-hydro, and OSW (ocean, solar and wind) also engendered interests from the private sector. Private investments on geothermal energy are significant as manifested by past capacity additions and proposed project developments in the medium term. The incentives for mini-hydropower development were introduced more than 10 years ago but it only generated modest investments from the private sector. The wind energy development incentives appear to attract more interest from the private sector as the government is aggressively opening areas with high wind power potential for development concessions. To enhance private investments, the government must formulate new frameworks and mechanisms that are consistent with the emerging competitive electricity market.

Table 4: Market deployment of renewables

<table>
<thead>
<tr>
<th>Country</th>
<th>Program Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malaysia</td>
<td>Small Renewable Energy Producers (SREP) Program</td>
<td>- as of January 2005, 62 projects were approved with aggregate capacity of 355 MW; 2 projects were commissioned in 2004 with total capacity of 12 MW.</td>
</tr>
<tr>
<td>Philippines</td>
<td>Minihydro Incentives</td>
<td>- As of 2003, 52 mini-hydro projects with total installed capacity of 77 MW; 4 on-going private investor-owned projects</td>
</tr>
<tr>
<td></td>
<td>Geothermal Incentives</td>
<td>- As of 2003, 1175 MW capacity is developed by state-owned PNOC-EDC while 757 MW capacity is developed by private investors.</td>
</tr>
<tr>
<td></td>
<td>Wind Power Incentives</td>
<td>- 3 projects with total capacity of 0.21 MW; one on-going private sector project with total capacity of 25 MW</td>
</tr>
<tr>
<td>Thailand</td>
<td>Small Power Producers (SPP) Programme</td>
<td>- For the period 1992-2002 - 50 projects with total capacity of 3.5 GW, of which 23 projects with capacity of 509 MW were renewable energy-based.</td>
</tr>
<tr>
<td></td>
<td>SPP Subsidy results in 2002</td>
<td>- Status in 2004 - total of 38 RE projects with total capacity of 914 MW</td>
</tr>
<tr>
<td></td>
<td>Very Small Power Producers (VSPP) Programme</td>
<td>- the programme targeted around 300 MW capacity additions through subsidy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 31 projects were proposed with total capacity of 511 MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 14 projects were selected in 2003 with aggregate capacity of 194 MW</td>
</tr>
</tbody>
</table>

Sources: Author’s compilation

7. Conclusion

Malaysia, Thailand and the Philippines enter into an exciting period for the development of their green power markets. The key lesson that could be learned from these countries’ experiences shows that grid access programmes supported by investment incentives and financial assistance set off the development of green power markets. As these countries gain more experience in renewable energy development, their renewable energy frameworks appear to converge.

To sustain the development of the market, governments must adopt innovative policy mechanisms that are consistent with their electricity markets. Thailand has recently adopted renewable portfolio standards (RPS). The full implementation of Thailand’s RPS could act as an impetus for the countries in the region to reassess their renewable energy frameworks and adopt more effective regulatory measures. The Philippines pending renewable energy bill has outlined RPS to be one of the government’s regulatory options to promote the sustainable development of green power markets. This also gives a small indication that obligation is preferable in the region than incentive tariffs.

RPS is a small step towards development of tradable certificates. This could be a natural evolution of policy strategy development in the region, though it may take a decade before this strategy could be adopted since countries must first strengthen their institutional capacities. However, this could be accelerated as various institutions gain more technical experience in implementing power industry reforms, particularly with the introduction of competitive markets, and in participating in trading of greenhouse gas emissions reductions under the Kyoto Protocol or other regional markets.
References


Financial Mechanism for PV Solar Home Systems Market Development; An Indian Case Study

Jyoti Prasad Painuly
Senior Energy Planner, UNEP Risø Centre on Energy, Climate and Sustainable Development, Risø National Laboratory, Roskilde-4000, Denmark. j.p.painuly@risoe.dk.

Abstract:

Rural electrification through grid extension has not made electricity available to the rural households in India, where still approximately seventy percent of them have no access to electricity. These households continue to rely on less efficient and polluting energy sources, typically biomass for cooking and heating and kerosene for lighting. Even though some of them are connected to grid, problems of capacity shortages and inconsistent quality plague the power supply, especially in rural and semi urban areas in most parts of India. Despite high initial costs, Solar Home Systems (SHS) emerge as an attractive option in the context of costly or unreliable alternatives and escalating grid power tariffs. Barrier to the growth of SHS market include a lack of access to financing, awareness, and risk perception associated with the technology, new to the customers of SHS and financing community. To address these barriers, consultations with stakeholders were held, that included manufacturers, financing institutions, and others. An intervention was designed based on the discussions and a credit facility created in partnership with two banks having wide reach to the potential customers in Karnataka State of India. The facility provides loan to the customers and a small subsidy to buy down high cost of the credit, which is designed to reduce over the three-year operation of the facility, with a target to reach market rates of interest at the end of the project. Technical support, awareness raising strategies and training were included as a part of the overall strategy. The credit facility was launched between April and June 2003 by the two partner banks. Early indications on sales have been very encouraging and the facility has already surpassed the target of 5000 SHS sales in two years within a year. Feedback mechanisms such as customer surveys, new initiatives to reach the poor households, and ongoing consultations with stakeholders etc. are also part of the market development strategy.
1 Introduction

Renewable Energy (RE) is expected to contribute significantly in future to World Energy Supply. Though estimates vary, studies indicate significant growth potential for renewables, particularly in scenarios where environmental constraints are imposed, for example on CO₂ emissions. According to IEA estimates, a scenario that considers new energy and environment policies in OECD countries, the share of renewables could reach 25 percent by 2030 (IEA, 2002).

The implication of the growing share of world energy needs mean RE can be expected to have a substantial share of energy sector investment which in total is estimated to be US$16 trillion over the next 30 years, 60% for the electricity sector alone. This is three times the amount invested in the last 30 years, and is due to the expected doubling of global electricity demand. The investment potential is huge even if renewables were to capture only 3-5% of this market. According to IEA (2002), globally installed renewable energy capacity is expected to more than double over the next ten years from approx. 130 GW in 2003 to 300 GW in 2013. Renewable energy is thus a multi-billion dollar industry and the most dynamic sector of the global energy market.

About seventy percent of rural households still without access to electricity in India, depend on less efficient and polluting energy sources – typically biomass for cooking and heating, and kerosene for lighting. This dependence on poor-quality forms of energy not only has impacts on health – for example, through increased incidence of respiratory diseases – but also limits both economic and social development.

Even when connected to the grid, problems of capacity shortages and inconsistent quality plague the power supply, especially in rural and semi urban areas in most parts of India. This has led households to look to alternative power supply systems such as inverters, diesel generators, and solar PV systems.

Access to modern energy through renewables in such cases can help socio-economic development through promotion of income generating activities and also reduce the adverse effect of fossil fuel energy use on the local and global environment. Increased use of RE can also help reduce dependence on imported fuels, market volatility of which could lead to energy security problems and consequent harmful impact on the economy.

India has one of the most comprehensive RE development programme among the developing countries with a full-fledged Ministry of Non-Conventional Energy Sources (MNES) dedicated to the promotion of RE. The MNES Policy Statement on Renewable Energy includes meeting minimum rural energy needs, providing decentralised / off-grid energy supply for agriculture, industry, commercial and household sectors in rural and urban areas; and, generating and supplying quality grid power. The medium-term goals, to 2012, include 10% of new power capacity addition from renewables, progressive electrification by renewables of 18,000 villages in remote areas, deployment of five million solar lanterns, two million solar home lighting systems, and one million solar water heating systems in the household segment (MNES, 2002-03 and IEA, 2001).

2 Barriers to Market Development

The RE market is still nascent and needs to be proactively developed if the huge potential it offers is to be realised. The barriers to RE have been discussed in detail in RE literature. An overview of important barriers to REs is shown in Figure 1.

In the initial stages of development, technical barriers predominate. Next, a variety of market barriers become major hindrance in realizing the full market potential a technology may offer. The market barriers not only reduce the size of market, but also reduce the economic potential by driving up the cost of technology. The market size depends on how successfully the barriers are addressed. Institutional, political and legislative barriers hinder the market penetration of technologies. These tend to arise from a lack of awareness of, and experience with, new technologies, and the absence of a suitable institutional and regulatory structure. There may be also social and environmental barriers, which result mainly from a lack of experience with planning regulations that hinder the public
acceptance of a technology. A sound strategy to increase market penetration of renewables will need to address all these barriers. A variety of intermediations such as technical, organisational, social, and financial can be considered depending on specific requirement of a renewable energy technology (Barnett, 1998).

Cost of renewable energy technologies (RET) has turned out to be the most important barriers to its dissemination in recent years. One reason for this is subsidies and other support mechanisms, including a well-developed infrastructure for the conventional fuels. Environmental costs are also not included in energy pricing, which favours conventional fuels. The high cost of renewables and perceptions about the technology make it difficult for RETs to access finance. As a result, financial barriers appear to be most prominent for developing renewables. Several financial support programs have been taken up by international agencies and public as well as private funds have been created to provide access to finance (Wohlgemuth and Painuly, 1999). A detailed discussions on renewable energy policies and barriers, including approaches adopted by various countries, can be found in Beck and Martinot (2004). In case of solar home systems (SHS), focus of a number of programs has been on development of infrastructure and supply side of the renewable energy. Although this approach successfully created a vibrant supply side, the market growth remained stunted due to inadequate attention to the demand side of the market, especially credit market.

**Figure 1. Impact of barriers on the market**
3 Experiences in Developing Countries

India has one of the most comprehensive RE programme, which includes promotion of SHS also. The support has been through capital subsidy. The market remained limited to the sales through the programme, which was constrained due to limited budget available for the subsidy. The credit market also did not develop as capital subsidy distorted the market. Cumbersome process to claim subsidy, delays in subsidy disbursal, and condition to supply SHS at prices fixed by the government (disregarding the quality differentials in products and services both) are considered other shortcomings of the governmental programme.

PV Market Transformation Initiative (PVMTI) was launched by the IFC in 1998 with a $15 million budget for India (of the total $30 million). Recently progress was made with fund commitments reaching $20 million. The PVMTI programme would further strengthen the infrastructure and supply side of the SHS in the three participating countries. The Solar Development Group (SDG), developed by the World Bank and IFC along with a number of charitable foundations and the GEF in 1999, is also expected to support development of PV related companies with a funding of about $50 million.

Grameen Shakti’s SHS programme in Bangladesh is considered one of the most successful programmes in developing countries. 23500 SHS had been installed until April 2004 with a target to reach 100,000 by 2008 (Barua, 2004). Starting operations in 1996, Grameen Shakti (GS) had planned to install 100,000 systems by 2000 (Lewis, 1997) but found the process of building customer confidence in systems time consuming and costly. In addition, long distances, poor transport infrastructure, impassable roads during monsoons, low literacy rates, cash-and-barter based transactions and lack of technical skills, all contributed to the high transaction costs of operating the rural PV business (G8 Renewable Energy Task Force, 2001). In 1998, International Finance Corporation (IFC) provided access to GEF funds through its Small and Medium Enterprises (SME) program, which enabled GS to offer better credit terms to their customers and their sales figures reached 2000 systems by the year 2000. The financing scheme that started with 50% of the system price as down payment and the remaining 50% in 6 months in six equal monthly instalments was modified from time to time and one of the option offered now requires only 15% of the system cost as down payment and the remaining 85% can be paid within 3 years time in equal monthly instalments with 12% service charge on the outstanding amount.

GS model has shown that learning from experiences can eventually lead to success. However, GS also takes responsibility for maintenance, and is the only credit-financing agency for SHS in Bangladesh. However dependence of the entire SHS programme on single agency, for financing as well as for services such as maintenance may not augur well for growth of a vibrant market in long term. The efforts should be made to replicate and diversify sources of financing and services within Bangladesh. Also, it is not clear if programme is fully commercial or still receiving some support.

GEF and the World Bank supported Sri Lanka Energy Services Delivery (ESD) Project that was implemented during 1997-2002 is also considered one of the successful SHS project. 20953 SHS had been installed during the programme and provision of consumer credit through micro finance providers, who work closely with solar companies, is considered most successful part of the model (Nagendran, 2004). A new project Energy for Rural Economic Development (RERED) Project, which aims to expand the commercial provision and utilisation of renewable energy resources, has since been initiated and is being implemented over the period 2002-2007. The ESD programme was implemented using GEF grant and IDA credit line and RERED project also heavily relies on GEF grant and IDA credit line, indicating that a commercially viable SHS (as well as RE) market run by local financing institutions is still not a reality in Sri Lanka. Fund commitment by the local financing institutions also needs to be ensured for sustainability after the project has ended.

The World Bank had also initiated a $118 million project in 1997 with GEF grant of $24 million, and target to install 200,000 SHS. The project faced rough weather during South Asian crisis, and was

---

1 Also see [http://www.energyservices.lk/offgrid/solarintro.htm](http://www.energyservices.lk/offgrid/solarintro.htm)
eventually closed in 2003 with about 8000 systems installed and budget substantially reduced; the GEF grant component also reduced to $4.5 million. The project however successfully created supply infrastructure for the SHS. In absence of credit sales, market for SHS is yet not fully developed.

There are several other GEF projects implemented by the World Bank to support SHS development in developing countries, details of which can be found in Martinot et. al. (2000).

4 The Project Setting and Strategy

4.1 Project setting

Despite the high initial cost, a PV solar home system could be an attractive long-term option, when compared with costly or unreliable power supplies; by way of example, Table 1 gives costs for a household with four lights, using either conventional fuels or SHS.

Table 1: Monthly Costs in Rupees for a Household with 4 lights (in 2002 in the state of Karnataka, India)\(^2\)

<table>
<thead>
<tr>
<th>Period</th>
<th>Existing Grid Customer</th>
<th>New Grid Customer(^1)</th>
<th>Kerosene</th>
<th>Inverter(^2)</th>
<th>SHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 5 years(^3)</td>
<td>115</td>
<td>297</td>
<td>212</td>
<td>465</td>
<td>325</td>
</tr>
<tr>
<td>10 years</td>
<td>148</td>
<td>298</td>
<td>272</td>
<td>465</td>
<td>200</td>
</tr>
</tbody>
</table>

Note: 1 USD = Rupees 45 (approx.)
1. New electricity grid customer incurs higher costs compared to an existing grid customer since the former has to pay for cost of connections from the nearest pole in the village.  
2. Cost of the equipments is included in the figures.  
3. Assuming grid and kerosene tariffs escalate @ 10% p.a. and grid customers pay at the higher tariff slab.

Without financing, however, the high initial cost of systems constrains the growth of the Indian SHS market. Increased access to credit could enable rural households to buy cleaner energy, and then pay for it with the money they are currently spending on less efficient – and often more polluting – forms of energy.

SHS are however yet to be established as a mainstream electrification technology, in part due to limited access to financing. India has a well-developed rural banking infrastructure, although its links to the renewable energy sector had yet to be consolidated. It was therefore concluded that a short-term intervention was needed - to address the issue of risk perception by banks, to increase consumer access to credit, and initially to lower the cost of this credit. Once these key barriers are addressed, it is expected that the market will begin to expand without further external support. Therefore, the objective of the project is to help Indian banking partners develop lending portfolios specifically targeted at financing solar home systems in poorly served regions of South India. It was also decided to keep the focus of the project on the poor in rural and semi-urban areas, who bear the brunt of power shortages and have limited access to expensive alternatives. It is expected that the long-term result of the project will be improved access to modern and clean electricity services for poorly served rural and peri-urban Indian households and small enterprises. The project is also attempting to contribute to poverty alleviation efforts by the Government of India with a strategy to reach the poor through both local Grameen banks and group lending via Self Help Groups (SHGs). Increased confidence and lending for solar electrification services would mean the expansion of sustainable energy in South India.

4.2 Project Strategy

Consultation with Stakeholders: Consultations with a wide range of stakeholders in South India, which included SHS vendors, banks and other small scale financing institutions, governmental

---

agencies, experts, NGOs etc., were carried out during the planning phase of the project. The findings from stakeholder discussions indicated that there is a strongly felt need for SHS in areas with non-existent or erratic electricity grid. Strong motivators for the use of SHS were children’s education, other lighting needs, and TV. A lack of availability and the cost of credit emerged as two major barriers to the wide scale adoption of SHS by potential buyers. It was also observed that although banks had enough credit available and were seeking new loan products, they were not yet ready to treat SHS as a standard technology. But the banks were ready to experiment and explore the possibility of scaled up lending for SHS.

The risk perception of the financial community, the high up-front cost of SHS, the high cost of credit and a lack of awareness among potential users were other barriers identified during the consultations.

Selection of Project Partners: The stakeholder consultations were carried out in three southern states of India but Karnataka was finally selected to implement the project in the initial phase. Karnataka has a strong rural banking system and also strong presence of best SHS vendors with good after-sales service network- thus providing a good infrastructure to launch the project. Canara Bank and Syndicate Bank, two large Indian retail banks with networks of branches in most parts of South India, were chosen as the partner banks. The banks support Regional Rural Banks (RRBs or Grameen banks) and hence have considerable coverage in the more rural areas.

Financing Mechanism: A number of market development models were considered during project preparation, including providing capital cost subsidies to solar vendors, end-user subsidies directly to customers, or financing subsidies through one or two partner banks. It was determined that direct links with vendors or customers were not necessary, and that working through the banks would be the most effective approach. It was felt that it would avoid the pitfalls associated with capital subsidies- their tendency to stick and distort the market. Results of stakeholder consultations as well as bankers preferences also indicated need for interest rate subsidies. An interest rate subsidy also reduces the project risk, it can be gradually reduced and withdrawn fully without significantly damaging the market.

The interest subsidy allowed the partner banks to offer loans to customers at concessional rates of interest, initially about 7% below their prime-lending rate of 12%. A corpus of USD 0.9 million for this purpose was expected to finance approximately 18,000 to 20,000 SHS. As the subsidies could be phase out over time, the actual number of SHS financed could be expected more, depending on the timing of the phase-out.

The project, by providing loans with an interest rate buy-down, addresses the ‘high up-front cost’ and high credit cost, the barriers identified by stakeholders. The project is expected to help increase awareness and confidence in SHS technology, bring down the financing costs of the technology in India, and widen the market.

A Free Market Approach: It was decided to work with as many vendors as could meet the product quality and after-sales service criteria. This leaves room for vendors to innovate in product/service offerings and for consumers to choose the system most appropriate for their needs and budgets. The panel of qualified vendors has been kept open for new vendors to be included as and when they are able to meet the criteria. Thus competitive forces are being used to ensure quality products, competitive pricing and reliable after-sales support. However, due to limited size of the corpus it was decided to work in partnership with only two banks.

Technical Support and Awareness Raising: An important component of the strategy was to provide support to the banks by providing standard specifications for SHS equipment and vendor qualification process. This addressed the problem of risk perception and also reduced transaction costs in processing the loans. Support for awareness programmes has also been provided, which include training programme for bankers and village level meetings between vendors, banks and potential customers.

Feedback: Periodic customer surveys are used to gain feedback from customers, and periodic audits for relevant checks are part of the project design. These are used to take corrective actions. A recent audit indicated the need for some corrections, which have now been initiated.
5. Results so far and challenges

The project was formally launched by the partner banks; Canara Bank in April 2003, and the Syndicate Bank in June 2003. Four solar vendors had met the qualification criteria and could send their customers to either Canara or Syndicate bank branches for SHS financing. The project plan set a target to finance 5,000 systems over the first two years, and 18,000 over the three and a half year project. Prior to the project, only about 1,400 SHS had been financed in Karnataka. By end of March 2005, the project had financed nearly 14,000 loans, through more than 2,000 participating bank branches, the fastest growth being in rural areas, in part to the increasing participation of the nine Grameen banks. The project has therefore exceeded the initial targets, and if the current momentum continues, can be expected to finance between 20,000-25,000 solar home systems, making it one of the largest SHS loan programmes globally (UNEP, 2005).

Phasing Out Interest Subsidies: The interest subsidy phase out started with first increase in interest rate to 7 percent to end users in October 2004- about one and a half year of launch of the project. The first reduction in subsidy did not have any adverse impact on the SHS sales, indicating credit availability as the major issue. A second increase is scheduled during 2005, which would take the user rates to 9-10 percent, close to the levels currently offered by the competing banks. The competition started when encouraged by the success of the banks in the project, some other banks launched their own loan schemes for SHS at competitive interest rates. This gradual removal of subsidies will enable the project to withdraw subsidy without significant adverse impact on the market.

Replication: Other banks operating in Karnataka, including Vijaya Bank, Corporation Bank, Karnataka Bank and Krishna Grameen Bank, had approached the UNEP to include them in the project. Only technical assistance was offered due to budgetary constraints. Several banks in Karnataka State have launched their own loan schemes for SHS indicating replication strategy is working. The partner banks have also launched loan scheme in other areas without interest subsidy.

Interestingly, the level of ‘total’ subsidy provided through the interest subsidy is much less than with other approaches. For instance, the 7% interest rate subsidy initially provided by the project equates to about 16% of total loan capitalization, and also therefore equates to a leverage for the project resources starting at 6:1, growing over time as the subsidy is phased out. Typically, in partial risk guarantees provide a ‘risk subsidy’ that is normally in the 30%-50% range, and therefore leverage of 2:1 or 3:1, although this also grows over time if loan defaults remain low. Capital subsidy programmes range considerably; in India they are above 50%, entailing a leverage of less than 1:1. A lesson; it’s not so much the extent of support provided, but rather the way in which it is provided that can determine the overall positive (or negative) impact on sector growth.

The challenge remains to persuade one of the partner banks, who has used up the entire fund available to him, continue lending at competitive rates. This is because steep increase in lending rates at this stage can impact the SHS sales adversely.

6 Conclusions

RE has tremendous potential to provide energy and electricity to the people in developing countries who lack access to modern energy sources. The high cost of RE compared to conventional energy is still a matter of concern in many parts of the world including India but with the right approach, Solar Home Systems can fill the gap and provide access to modern energy to a large number of households, particularly those in rural areas who lack access to electricity. A properly designed programme, involving stakeholders during design as well as execution stage, can help develop markets for RE, as evident from early indications from the project in India. Continuous monitoring and involvement of stakeholders at all stages of execution remains key to good programme progress. Eventual success of the project will be however assessed in its ability to transition the market from a subsidised to commercial market. This has been considered in the project design by gradually increasing the interest

3 Some details can be found in an earlier version of the paper Painuly and Usher (2004).
rate to market rates. The expanded market for vendors, coupled with confidence of the financing institution is expected to ensure that cost to the consumers may not appreciably change even after the project has ended.

Acknowledgements: The project has been supported by funds from UN Foundation and Shell Foundation. The data on SHS sales and other items has been provided by partner banks in India; Canara and Syndicate Bank, and the vendors, viz., Selco Solar Light India, Shell Solar India, Tata BP Solar India and Kotak Urja, India. Project is supported by Eric Usher in UNEP Paris and by Crestar Consultants, India.

7 References:


### List of participants

<table>
<thead>
<tr>
<th>Last name</th>
<th>First name</th>
<th>Company</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andersen</td>
<td>Frits Møller</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Andersen</td>
<td>Jan</td>
<td>Roskilde University</td>
<td>Denmark</td>
</tr>
<tr>
<td>Andersen</td>
<td>Per Dannemand</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Arndt</td>
<td>Morgens</td>
<td>Energi E2</td>
<td>Denmark</td>
</tr>
<tr>
<td>Ashwill</td>
<td>Thomas</td>
<td>Sandia National Laboratories</td>
<td>USA</td>
</tr>
<tr>
<td>Astrup</td>
<td>Thomas</td>
<td>Environment &amp; Resources DTU</td>
<td>Denmark</td>
</tr>
<tr>
<td>Barthelmine</td>
<td>Rebecca</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Bechraoui</td>
<td>Nadia</td>
<td>United Nations Development Programme</td>
<td>Tunisia</td>
</tr>
<tr>
<td>Bentzen</td>
<td>Janet Jonna</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Bergstrom</td>
<td>Willy</td>
<td>NESA A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Biancardo</td>
<td>Matteo</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Bida</td>
<td>Amel</td>
<td>National Agency of Energy Conservation</td>
<td>Tunisia</td>
</tr>
<tr>
<td>Binder</td>
<td>Henrik</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Birol</td>
<td>Fatih</td>
<td>International Energy Agency (IEA)</td>
<td>France</td>
</tr>
<tr>
<td>Christensen</td>
<td>Ditte Vesterager</td>
<td>Roskilde University</td>
<td>Denmark</td>
</tr>
<tr>
<td>Christensen</td>
<td>John M.</td>
<td>UNEP Risø Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Clausen</td>
<td>Niels-Erik</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Coenen</td>
<td>Peter</td>
<td>VITO</td>
<td>Belgium</td>
</tr>
<tr>
<td>Cronin</td>
<td>Tomas</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Cutululis</td>
<td>Nicolaos Antonio</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Dando</td>
<td>Lori Peterson</td>
<td>U.S. Embassy Copenhagen</td>
<td>Denmark</td>
</tr>
<tr>
<td>Davidson</td>
<td>Ogunlade</td>
<td>University of Sierra Leone</td>
<td>Sierra Leone</td>
</tr>
<tr>
<td>Dhaeseleer</td>
<td>William</td>
<td>University of Leuven</td>
<td>Belgium</td>
</tr>
<tr>
<td>Eliker</td>
<td>Jørgen</td>
<td>Dansk Metal</td>
<td>Denmark</td>
</tr>
<tr>
<td>Fonnesbech</td>
<td>Bjarke</td>
<td>The Danish Society of Engineers</td>
<td>Denmark</td>
</tr>
<tr>
<td>Frisbæk</td>
<td>Fanny</td>
<td>Hönnun hf</td>
<td>Iceland</td>
</tr>
<tr>
<td>Garg</td>
<td>Amit</td>
<td>UNEP Risø Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Gebart</td>
<td>Rikard</td>
<td>ETC</td>
<td>Sweden</td>
</tr>
<tr>
<td>Gehrke</td>
<td>Oliver</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Giebel</td>
<td>Gregor</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Gielen</td>
<td>Dolf</td>
<td>International Energy Agency (IEA-EET)</td>
<td>France</td>
</tr>
<tr>
<td>Giovanniotti-Sermanni</td>
<td>G.</td>
<td>University of Tuscia</td>
<td>Italy</td>
</tr>
<tr>
<td>Gut</td>
<td>Beat</td>
<td>Fucellco AG</td>
<td>Switzerland</td>
</tr>
<tr>
<td>Haagensen</td>
<td>Frank</td>
<td>Technical University of Denmark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hagen</td>
<td>Anke</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hake</td>
<td>Jürgen-Fr.</td>
<td>Forschungszentrum Jülich</td>
<td>Germany</td>
</tr>
<tr>
<td>Hall</td>
<td>Peter</td>
<td>Member of Parliament</td>
<td>Australia</td>
</tr>
<tr>
<td>Hamanda</td>
<td>Ana-Mari</td>
<td>EARTH University</td>
<td>Germany</td>
</tr>
<tr>
<td>Hansen</td>
<td>Anca</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hansen</td>
<td>Jens Carsten</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hartmann</td>
<td>Hinrich</td>
<td>Technical University of Denmark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hauch</td>
<td>Anne Belinda</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Helynen</td>
<td>Satu</td>
<td>VTT Processes</td>
<td>Finland</td>
</tr>
<tr>
<td>Henningsen</td>
<td>Jørgen</td>
<td>Weatherhead Center for International Affairs</td>
<td>USA</td>
</tr>
<tr>
<td>Name</td>
<td>First Name</td>
<td>Affiliation</td>
<td>Country</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------</td>
<td>-------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Henrichsen</td>
<td>Henrik</td>
<td>University of Southern Denmark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Henriksen</td>
<td>Niels</td>
<td>Elsam A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hesseldahl</td>
<td>Peter</td>
<td>Danfoss Universe</td>
<td>Denmark</td>
</tr>
<tr>
<td>Hinstrup</td>
<td>Peter I.</td>
<td>Danish Gas Technology Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Holst-Jensen</td>
<td>Jens</td>
<td>Energi Industrien</td>
<td>Denmark</td>
</tr>
<tr>
<td>Høstgård-Jensen</td>
<td>Peter</td>
<td>ELSAM A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Ipsen</td>
<td>Karen Hvid</td>
<td>Elsam Engineering</td>
<td>Denmark</td>
</tr>
<tr>
<td>Iskov</td>
<td>Henrik</td>
<td>Danish Gas Technology Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Janeiro</td>
<td>Vasco de Oliveira</td>
<td>EURELECTRIC</td>
<td>Belgium</td>
</tr>
<tr>
<td>Jensen</td>
<td>Erik Steen</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Jensen</td>
<td>Søren Byrial</td>
<td>Elsam Engineering</td>
<td>Denmark</td>
</tr>
<tr>
<td>Jensen</td>
<td>Stine Grena</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Jimenez</td>
<td>Alethia</td>
<td>Rochester Institute of Technology</td>
<td>USA</td>
</tr>
<tr>
<td>Johnson</td>
<td>Mike</td>
<td>CCLRC Rutherford Appleton Laboratory</td>
<td>England</td>
</tr>
<tr>
<td>Jordan</td>
<td>Thomas</td>
<td>Forschungszentrum Karlsruhe</td>
<td>Germany</td>
</tr>
<tr>
<td>Jørgensen</td>
<td>Birte Holst</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Jørgensen</td>
<td>Ulrik</td>
<td>Technical University of Denmark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Kjær</td>
<td>Sven</td>
<td>Elsam Engineering</td>
<td>Denmark</td>
</tr>
<tr>
<td>Kjems</td>
<td>Jørgen</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Koch</td>
<td>Jesper</td>
<td>Association of Danish Energy Companies</td>
<td>Denmark</td>
</tr>
<tr>
<td>Kolijonen</td>
<td>Tiina</td>
<td>VTT Processes</td>
<td>Finland</td>
</tr>
<tr>
<td>Laird</td>
<td>Daniel</td>
<td>Sandia National Laboratories</td>
<td>USA</td>
</tr>
<tr>
<td>Larsen</td>
<td>Hans</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Lauritsen</td>
<td>Sigurd</td>
<td>Ramboll</td>
<td>Denmark</td>
</tr>
<tr>
<td>Lauritzen</td>
<td>Hanne</td>
<td>Danish Technology Institute</td>
<td>Denmark</td>
</tr>
<tr>
<td>Lawaetz</td>
<td>Henrik</td>
<td>Danish Energy Authority</td>
<td>Denmark</td>
</tr>
<tr>
<td>Sønderberg Petersen</td>
<td>Leif</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Lilholt</td>
<td>Hans</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Lundsager</td>
<td>Per</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>Gordon</td>
<td>UNEP Riso Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Madsen</td>
<td>Peter Hauge</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Majborn</td>
<td>Benny</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Markert</td>
<td>Frank</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Markussen</td>
<td>Peter</td>
<td>Elsam A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Marzouk</td>
<td>Hatem</td>
<td>European Institute for Energy Research</td>
<td>Germany</td>
</tr>
<tr>
<td>Meibom</td>
<td>Peter</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Mogens</td>
<td>Mogensen</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Morsing</td>
<td>Vivi Nymark</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Morthorst</td>
<td>Poul Erik</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Mulavana Parameswaran</td>
<td>Ram Mohan</td>
<td>The Energy and Resources Institute</td>
<td>India</td>
</tr>
<tr>
<td>Münster</td>
<td>Ebbe</td>
<td>PlanEnergi</td>
<td>Denmark</td>
</tr>
<tr>
<td>Neff</td>
<td>H.J.</td>
<td>Forschungszentrum Jülich</td>
<td>Germany</td>
</tr>
<tr>
<td>Nielsen</td>
<td>Charles</td>
<td>Elsam Kraft A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Nielsen</td>
<td>Poul Erik Højlund</td>
<td>Haldor Topsøe A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Nielsen</td>
<td>Steen Broust</td>
<td>LM Glasfiber</td>
<td>Denmark</td>
</tr>
<tr>
<td>Nikolaisen</td>
<td>Lars</td>
<td>Danish Technological Institute</td>
<td>Denmark</td>
</tr>
<tr>
<td>Nissen</td>
<td>Flemming</td>
<td>Elsam A/S</td>
<td>Denmark</td>
</tr>
<tr>
<td>Nørgård</td>
<td>Per B.</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Pacudan</td>
<td>Romeo</td>
<td>UNEP Riso Centre</td>
<td>Denmark</td>
</tr>
<tr>
<td>Pedersen</td>
<td>Aksel Hauge</td>
<td>DONG VE</td>
<td>Denmark</td>
</tr>
<tr>
<td>Pedersen</td>
<td>Allan Schroder</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Pedersen</td>
<td>Erik Lundtang</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Petersen</td>
<td>Jon Wulff</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
</tr>
<tr>
<td>Name</td>
<td>Affiliation</td>
<td>Country</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>Poulsen Annette Bagge</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Poulsen Hans Henrik</td>
<td>Burmeister &amp; Wain Energy A/S</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Prasad Painuly Jyoti</td>
<td>UNEP Risø Centre</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Pryor Sara</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Qvale Bjørn</td>
<td>Technical University of Denmark</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Radka Mark</td>
<td>UNEP</td>
<td>France</td>
<td></td>
</tr>
<tr>
<td>Rasmussen Hans Jørgen</td>
<td>DONG</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Ridell Bengt</td>
<td>Carl Bro Energikonsult AB</td>
<td>Sweden</td>
<td></td>
</tr>
<tr>
<td>Rise Søren</td>
<td>Danish Standards Association</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Röttger Ulla</td>
<td>Amagerforbrænding A/S</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Schaumburg-Müller Camilla</td>
<td>Technical University of Denmark</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Schmid Jürgen</td>
<td>ISET</td>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>Schock Robert</td>
<td>Center for Global Security Research</td>
<td>USA</td>
<td></td>
</tr>
<tr>
<td>Siala Fuad</td>
<td>OPEC</td>
<td>Austria</td>
<td></td>
</tr>
<tr>
<td>Sigfusson Thorsteinn</td>
<td>University of Iceland</td>
<td>Iceland</td>
<td></td>
</tr>
<tr>
<td>Sjunnesson Lars</td>
<td>Sydkraft AB</td>
<td>Sweden</td>
<td></td>
</tr>
<tr>
<td>Skea Jim</td>
<td>UK Energy Research Centre</td>
<td>England</td>
<td></td>
</tr>
<tr>
<td>Steen Peter Helmer</td>
<td>Danish Energy Authority</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Stehr Hans Jürgen</td>
<td>Danish Energy Authority</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Steiner Michael</td>
<td>Hahn-Meitner-Institute</td>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>Taylor Gordon</td>
<td>GT Systems</td>
<td>England</td>
<td></td>
</tr>
<tr>
<td>Tophøj Niels</td>
<td>Elsam Engineering</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Tronstad Tomas</td>
<td>Det Norske Veritas Research</td>
<td>Norway</td>
<td></td>
</tr>
<tr>
<td>Tüxen Erik</td>
<td>WINDTEST Kaiser-Wilhelm-Koog GmbH</td>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>Varga Enikö</td>
<td>Risø National Laboratory</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Vegge Tejs</td>
<td>Riso National Laboratory</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Venne Philippe</td>
<td>University of Quebec</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Vora Shailesh</td>
<td>Siemens Westinghouse Power Corp.</td>
<td>USA</td>
<td></td>
</tr>
<tr>
<td>Walton Philip</td>
<td>National University of Ireland</td>
<td>Ireland</td>
<td></td>
</tr>
<tr>
<td>Ybema Remko</td>
<td>Energy Research Centre of the Netherlands</td>
<td>The Netherlands</td>
<td></td>
</tr>
<tr>
<td>Yde Lars</td>
<td>HIH-Vind</td>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Åhman Max</td>
<td>Lund University</td>
<td>Sweden</td>
<td></td>
</tr>
</tbody>
</table>