Storage Utsira. Analysis of potentials and costs of storage of CO2 in the Utsira formation.

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Storage Utsira

Analysis of potentials and costs of storage of CO_2 in the Utsira formation

Country report – Denmark

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Abbreviations

CCGT	combined cycle gas turbine
CCS	Carbon Capture and Storage
CHP	combined heat and power
CO_2	carbon dioxide
ETP	Energy Technology Perspectives (IEA)
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
GEUS	Geological Survey ofr Denmark and Greenland
GIS	geographical information systems
GHG	Greenhouse gasses
Gt	Gigatonne
GW	Gigawatt
GWh	gigawatt hours
IEA	International Energy Agency
IGCC	Internal Gasification Combined Cycle power plant
IPCC	Ineregovernmental Panel on Climate Change
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hours
LHV	Lower heat value
MARKAL	Market Allocation (optimisation model developed by the IEA)
Mt	Megatonne
Mtoe	million ton of oil equivalent
MW	Megawatt
MWe	megawatt, electric
MWh	megawatt hours
NGCC	Natural Gas Combined Cycle power plant
PC	Pulverised coal-fired power plant
PET	Pab European TIMES (model)
PJ	Petajoule 10^{15} Joule
RES	Reference energy system
TIMES	The Integrated Markal EFOM System
TJ	Terajoule 10^{12} Joule
toe	ton of oil equivalent
TWh	terawatt hours 10^{12} Wh
VEDA	VErsatile Data Analyst
WEO	World Energy Outlook (IEA)

Project Partners

NO	Insititute for Energy Technology (IFE). Co-ordinator.
DE	Universität Stuttgart, Institute of Energy Economics and the Rational Use of Energy (IER)
DK	Risø DTU. Systems Analysis Division
NL	Utrecht Universiteit, Copernicus Institute for Sustainable Development and Innovation
UK	King's College/University College, London

Preface

This report is the main deliverable for Denmark in the project '*Analysis of potentials and costs of storage of CO_2 in the Utsira Aquifer in the North Sea'*. This project is funded by ForskEL/Energinet.dk – within FENCO-ERA, which is an EU network for national R&D activities in 13 countries in the field of fossil energy conversion and CO_2 capture and storage (CCS).

This project aims to analyze potential and costs of storage of CO_2 in the Utsira aquifer in the North Sea. In this project quantitative analyses of specific scenarios for five countries (Denmark, Germany, Norway, the Netherlands and the United Kingdom) that are surrounding the North Sea.

The work is organized into five work packages.

- WP1 Physical possibilities and constrains for CO_2 storage in the Utsira formation
- WP2 Inventory and harmonization of data and assumptions for CCS modelling and scenario development
- WP3 National modelling of CCS Pathways
- WP4. Analysis at the regional level (North Sea region)
- WP5 Possibilities, synergies and conflicts for a CO_2 pipeline in the North Sea

This report is one of the five country reports of WP3.

The model results presented in this report is based on the model analysis with the regional Pan European TIMES model for all five countries. This analysis was made by Markus Blesl and Tom Kober of IER, University of Stuttgart.

Since 2004 the Pan European TIMES model is being developed and enhanced within the IEA Implementing Agreement ETSAP and various projects supported by the EU. Recently, detailed results from the EU RES2020 project became available online, while the online availability of model assumptions and documentation of the VEDA database system is still under development.

An abstract "Carbon Capture and Storage: Modelling heat recovery by large district heating systems" has been submitted to the International Energy Workshop, Stockholm 20-22 June 2010. This workshop is held back to back with the IEA ETSAP semi-annual workshop.

Data for CO_2 storage potentials were provided by GEUS, Geological Survey of Denmark and Greenland

Mikael Lüthje, DTU Climate Centre has contributed to the last project meeting and review of reports.

Risø DTU, March 2010

Poul Erik Grohnheit

Executive Summary

So far there has been very little interest in CCS in Denmark. The technology is not a part of public policy, and the Government has not expressed any official standpoint on the use of CCS in Denmark. On the other hand, both the electricity industry and geologists from the Geological Survey of Denmark and Greenland (GEUS) have been active in international research on both capture and storage.

During the last three decades the key issue for location of thermal power plants has been the possibility to supply the heat market from combined heat and power. This means that the structure of thermal power plants reflects the structure of district heating networks and, thus, the urban structure. The most modern and efficient coal-fired power plants are located in six urban regions with district heating networks covering large shares of the heat markets. Smaller units – ranging from 50-100 MW combined cycle gas turbines to gas engine below 1 MW are located to supply a few hundred district heating networks and some industrial demand for heat or steam.

In recent years wind power has become an important part of the electricity generation in Denmark, covering some 20 % of the demand on an annual basis, but with variations on an hourly basis from no generation at all to generation larger than the national demand. The balancing of demand and supply is made by the thermal units connected to heat storages, international trade, and electricity demand response. The key instrument for the balancing is the Nordic electricity market, in particular the Nord Pool day-ahead market with hourly prices for the next 12-36 hours.

The role of wind power is planned to increase significantly over the next decades. This means that there will be less and less room for capital-intensive base-load units that must operate constantly, which is the usual concept for CCS technology. Thermal units will still be important, but they must meet the requirement for flexibility. In addition to flexible operation of electricity and heat, flexible operation of electricity and hydrogen may be developed in the future. Both these technologies may have a potential for flexible operation of carbon capture technologies.

There is a long tradition in Denmark for development and implementation of coal combustion technology for electricity – electricity-only as well as cogeneration with heat. The condensing – electricity-only efficiency of the 300-500 MW extraction-condensing units increased during the last decades from less than 40 % to 47 % at Nordjyllandsværket. The use of seawater cooling instead of cooling towers added some 1.5 %-points to the efficiency. Danish power companies have played a major role in a European project aiming at the development of coal-fired plants with steam temperatures of 700°C and significant increase of efficiency. Other important technologies have been urban waste incineration and large-scale combustion of straw.

Specifically on carbon capture, DONG Energy has taken part in the CASTOR project, which included a pilot plant at Esbjergværket in Denmark aiming at testing the reliability and efficiency of the post-combustion capture process. The test facility was finished in 2006, and four 1000 hours test campaigns were carried out the following year.

The total CO_2 emission from Denmark in year 2000, which is the starting year of the model study was 52.5 mill ton. Annual variations are significant, because electricity export from coal combustion varies with hydropower production in Norway and Sweden.

The CO_2 storage capacity onshore and near shore in Denmark is very large, some 16,000 mill. ton CO_2, while the offshore capacity in oil and gas fields in the Danish section of the North Sea is much smaller, only 828 mill. ton CO_2. These estimates are from the GESTCO project on the European potential for CO_2 storage, which was initiated by GEUS in 1999. GEUS was project leader of both GESTCO (completed in 2003) and the following GeoCapacity project (2002-2006) under the EU 6th Framework Programme with participation from most European countries. The latter project also contains a "conservative estimate of storage capacities, which is much lower. For Denmark this estimate is 2600 mill. ton in Aquifers and 200 mill. ton in hydrocarbon fields.

The estimate of the onshore storage capacity was based on a study focusing on 11 individual storage structures mainly in Jutland. In Vedsted, some 30 km from Nordjyllandsværket, Vattenfall started collecting new seismic data in September 2008 as a part of a full-scale project for capture, transport and storage to be available from 2013. However, in the Autumn 2009 it was decided to postpone this project.

For more than ten years the Government's official standpoint has been complete phase out of coal rather than support of CCS. In the same period the technology and infrastructure for biomass combustion has been further developed. This includes incineration of nearly all combustible municipal waste in some 30 waste incineration plants supplying base-load heat to the large district heating systems as well as an increasing amount of electricity. In addition, straw has become a significant fuel for several small-scale and a few large-scale CHP units. This opens for a vision of negative CO_2 emission, when combining biomass combustion and CCS.

A very significant additional constraint for CCS in Denmark is the planned development of wind power, which currently covers some 20 % of the annual electricity demand, but is planned to increase to more than twice as much. This will further reduce the need for base-load thermal electricity generation

For the model analysis in the Storage Utsira project it means that the potential for CCS is becoming increasingly constrained. To model these constraints, it means that the Pan European TIMES model, which has a structure that is harmonised to meet the requirements for 30 European countries, must be calibrated in further details for give a proper representation of the constrained potential for Denmark.

The large national potential for carbon storage and the very constrained potential for carbon capture makes it is very unlikely that Denmark will use a distant off-shore CO_2 storage capacity such as the Utsira formation within the time-horizon of the study.. However, in co-operation with other countries around the North Sea the Danish potential for carbon storage may contribute to the build up of the long-distanced CO_2 transport infrastructure. This issue should be addressed, when designing the infrastructure scenarios for the transport system that shall connect the countries around the North Sea with the Utsira formation, even when this option may not be chosen as an option to be included in model calculations.

1 Introduction

1.1 Project overview

The potential CO_2 storage capacity in the Utsira formation is estimated to be between 20 and 60 Gt CO_2 (Lindeberg et al., 2009) Thus, it is expected that the Utsira formation could be used as a CO_2 reservoir for at least 20-30 years for several European countries. The use of Utsira as a European reservoir will however not only depend on its available capacity to store CO_2 flows but mainly on the cost effectiveness of this option within (future) national portfolios of mitigation measures. Therefore, the possibility of storing CO_2 at Utsira (including the costs of the pipeline network) needs to be assessed taking into account national CO_2 reduction targets, temporal (e.g. development of the energy system and new CO_2 sources in each country) and spatial aspects (e.g. availability and location of local sinks and CO_2 sources over time).

In this project quantitative analysis of specific scenarios for Denmark, Germany, Norway, the Netherlands and the United Kingdom are carried out. The project has adopted a cost minimisation approach within the time horizon 2005 to 2050. Linear optimisation models such as MARKAL and TIMES are used to assess how national energy systems with a CO_2 infrastructure (including CO_2 transport to Utsira) can be developed against minimal costs. The results of this project will generate insights into the role that a mega-structure such as Utsira could play for CCS deployment in each country and in the North Sea region. Further, recommendations for appropriate capture technologies and infrastructure for CO_2 with their possible levels and timing for each of the countries around the North Sea will be generated.

This project aims to provide stakeholders with a detailed overview of the national and regional costs, benefits and bottlenecks of carbon capture and transporting and storing CO_2 from countries in the North Sea region into the Utsira formation. This is done by developing a modelling tool within the framework of the continued model development on the basis of the Pan European NEEDS-TIMES model and/or national MARKAL/TIMES models.

Sub-goals of the project are:

- Improved knowledge on uncertainties and limitations to use the Utsira Formation as a CO_2 reservoir (capacity, user conflicts, leakage problems etc)
- Improved knowledge on transportation alternatives and barriers (both technical and political/economical) including possible synergies and conflicts for constructing an international CO_2 pipeline network in the North Sea region.
- Coordinate analysis of CCS for the countries around the North Sea (Norway, Denmark, Germany, the Netherlands and the United Kingdom) for the time period 2015-2050, with a focus on the national and regional implications of offshore CO_2 transport to the Utsira formation.
- Analysis of techno-economic parameters of future carbon capture technologies and their impact on CCS market penetration, considering alternative carbon reduction measures in the context of the countries’ energy systems.

- Develop experience using the TIMES model for infrastructure development leading to an identification of a set of possible stepwise developments. (cf. the use of the term “pathway” below).

This report provides the results of the work conducted for the Danish energy system.

There are great differences among these five countries concerning electricity generation, the availability of domestic storage capacity and political commitments to CCS development. The storage capacities of Norway and Denmark are very large, but CO_2 emissions from electricity generation is either very small or decreasing, while Germany, the Netherlands and UK will remain very dependent on fossil fuels, but the domestic storage capacities are limited..

1.2 FENCO-ERANET

The Danish power system operator Energinet.dk is partner in The Fossil Energy Coalition (FENCO)-ERA NET initiative, which commenced in June 2005 and is supported under the ERA-Net scheme.

FENCO-ERA is a Coordination Action (CA) within the EU 6th Framework Programme. Project title: Promotion of an Integrated European and National R&D Initiative for Fossil Energy Technologies towards Zero Emission Power Plants.

The overall aim of FENCO-ERA is to network the national and regional R&D activities in the field of fossil energy conversion and carbon capture and storage (CCS) technologies in order to construct a durable ERA-NET. This topic is dedicated to examine the current state-of-the-art analysis of CCS technologies, to further develop economic modelling and to explore the economic potential of full deployment of CCS technologies within the portfolio of climate change mitigation options. It is further dedicated to analyse the economic potential of CCS under a wide range of socio-economic conditions, fossil fuel price developments and energy scenarios. This comprises following items for the different technology routes

- Cost concepts, cost modelling and learning curve concepts
- Incentive schemes to promote the deployment of CCS
- National energy systems models and scenarios e.g. Markal, TIMES or others

Denmark is among the 11 countries participating in FENCO-ERA. This includes all countries around the North Sea, which offers several possibilities for CO_2 storage.:

1.3 Pan European TIMES model

The Pan European TIMES model that was developed as a part of NEEDS and RES2020 covers now covers more than 30 countries. Model results from studies with time-horizon 2050 will select CCS technologies for most countries, when CO_2 emissions are constrained, but the experience from national model studies is dependent on national priorities.

1.4 Report Contents

Chapter 2 describes the Danish energy sector with emphasis on the structure of the power generating system..

Chapter 3 describes CCS policy and activities in Denmark and includes methods and data from the project partners that will be useful for modelling of CCS in Denmark.

Chapter 4 contains a short survey of models used for the Danish energy sector. So far none of these models have considered CCS. The Pan European model that is used for the regional study by IER, Stuttgart is described with emphasis on the CCS modelling.

Chapter 5 summarises the main scenario assumptions and the results from the interregional model covering all five countries in the project.

Finally *Chapter 6* summarises the main conclusions for Denmark.

2 Energy sector

Since the Mid 1970s the total primary energy consumption in Denmark has been about 800 PJ with annual variation that has been due mainly to variations in electricity trade with the hydro-based regions in Norway and Sweden. In the same period there has been a continuous development from about 90% imported oil to a more diversified supply of coal, oil gas and renewables.

Currently, Denmark is the only country within the EU that is a net exporter of oil and gas. Denmark's primary energy production of oil and gas from the North Sea has continued to increase steadily from 1980 to 2005. However, the production has peaked about 2005 and will decrease in the coming years due to depletion of the resources in the North Sea.

The natural gas infrastructure was built up during the 1980s and 1990s with transmission lines for export to Sweden and Germany and seasonal storages. The gas distribution network covers most of the country with supply to power stations, district heating plants, industries and individual homes in areas less suitable for district heating. The district heating infrastructure covers all the more densely populated urban areas, including small towns and villages. Base load heat in nearly all district heating networks is supplied CHP plants, ranging from less than 1 MW gas motors to large-scale power plants). Waste incineration for CHP or heat-only is used as base-load in all urban areas using about 95% of the available urban waste. From about 1980 all new power station have systematically been located to supply district heating systems with co-generated heat.

Wind power has grown constantly during the 1990s and covers about 20% of the electricity demand in the years 2004-2008 on an annual basis.

2.1 Development of electricity and heat supply

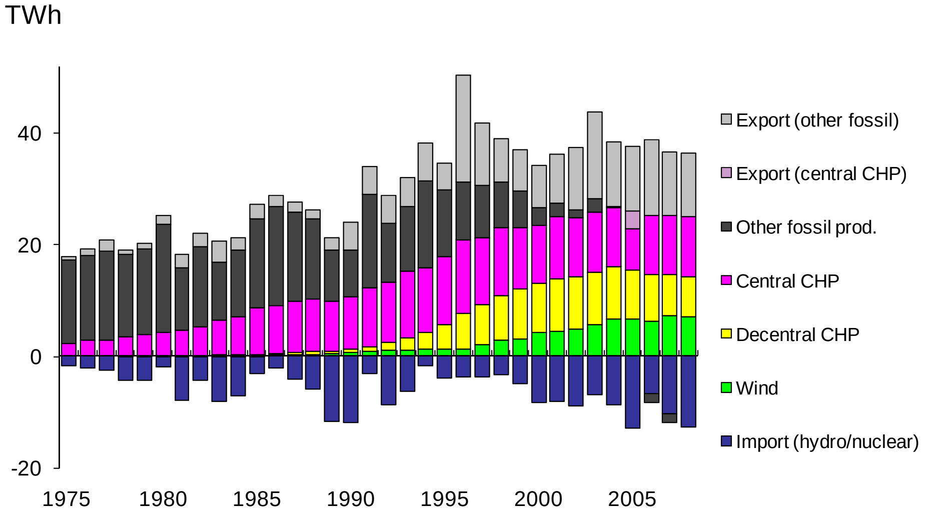


Figure 2.1. Electricity production and import, Denmark 1975-2008

Source: Danish Energy Association , Statistics and own calculations.

The figure shows the development of the Danish electricity generation during the last three decades. The two main characteristics are the fluctuation in international electricity trade and a steady increase in generation from large-scale and small-scale CHP and – more recently – also from wind. The electricity generation from CHP is linked to the infrastructure and demand for district heating, while the fluctuation in international electricity trade depends on the natural variations in precipitation – and, thus, hydro power generation in Norway and Sweden. In the very dry years 1996 and 2003 the electricity generation and export from Denmark was large, and in the wet years 1989, 1990, 2005 and 2008 the electricity import to Denmark was large.

After 1980 all new power station have been located systematically to supply district heating systems with co-generated heat. In the 1980s nearly all new capacity was medium-sized extraction-condensing units for large-scale CHP; in the 1990s a significant share was small-scale gas-fired CHP units for the smaller district heating systems in towns and villages. Wind power has grown constantly during the 1990s and has been nearly 20% of the electricity demand on an annual basis for several years before 2009.

The most suitable technology for CCS is modern extraction-condensing power plants, located for supply of the large urban district heating systems in Copenhagen, Odense, Aarhus, Aalborg, Esbjerg and the conglomeration of towns around the Little Belt bridges with the interconnected district heating transmission network TVIS, see Table 2.1.

The Copenhagen network is supplied mainly from two power stations, Amager and Avedøre and three waste incineration plants, one located at the Amager power station and two at separate sites. In addition, there are several gas or oil fired peak load units. The same structure is found in the other large systems, In addition to the power stations the very few large industrial plants are located in these areas: Cement in Aalborg, refineries in Fredericia (TVIS) and Kalundborg. The large heat supply for the small town of Kalundborg is explained by the ‘industrial symbiosis’ of the large coal-fired power plant, the refinery and several industrial plants, where waste from one plant is used as input for others.

The largest coal harbour in northern Europe is located at Enstedværket near Aabenraa with barge transport to other coal-fired power stations. At Stigsnæsværket, there is another harbour with large capacity for coal import, but its electricity generation is mainly for export in dry years, such as 1996, 2003 and 2006. The large capacity at Kyndbyværket is very important for peak load, but the annual production has been small during the last decades, even in dry years.

Table 2.1. Electricity and heat generation and capacities connected to interconnected district heating grids in Denmark

	Capacity, MW	Electricity, GWh		Heat, PJ	Emission, Mt CO2		
	2005	2005	2008	2005	2005	2008	GEUS
Copenhagen (Amager, Avedøre, etc.)	1479	5180	4972	24.1	4.2	4.1	5.93
Aarhus (Studstrupværket)	712	2239	2873	9.0	1.8	2.3	2.83
Odense (Fynsværket)	640	1828	2024	8.1	1.5	1.6	2.00
Aalborg (Nordjyllandsværket)	692	2281	2363	3.5	1.9	1.9	4.88
TVIS (Skærbækværket)	392	1176	1075	3.4	1.0	0.9	0.99
Esbjerg (Esbjergværket)	378	1731	1352	2.6	1.4	1.1	1.90
Kalundborg (Asnæsværket)	1057	2561	2537	2.1	2.1	2.1	3.54
Aabenraa (Enstedværket)	625	1105	2611	0.2	0.9	2.1	2.60
Stignæsværket	409	631	582	0.0	0.5	0.5	0.97
Kyndbyværket	734	48	42		0.0	0.0	0.07
Decentral CHP areas	2437	9186	7556	22.7	4.4	3.6	3.00
Total thermal generation	9555	27966	27988	75.8			
Wind (incl.hydro)	3146	6637	6954				
Total	12701	34603	34942	75.8	20	20	28.71

Future large power units with CCS as well as retrofit of existing units will be located at the stations connected to the large district heating networks,

More than hundred smaller CHP units, ranging from 100 MW combined cycle gas turbines to gas motors less than 1 MW are connected to smaller CHP areas. These units are fuelled mainly by natural gas, but the number of units fuelled by various types of biomass is increasing. In the future development of district heating many of these areas will be expanded by interconnection of smaller district heating systems or connection to the large systems, most important in the densely populated region north of Copenhagen. This will increase the heat markets connected to power stations suitable for CCS.

More energy efficient buildings in the future will reduce the demand for heat from the existing district heating networks. However, the share of district heating is planned systematically increased on the expense of natural gas, electric heating and individual oil burners. The most important alternative to district heating in future energy efficient buildings will be heat pumps.

In the next decades the share of wind power will gradually increase from 20 % to more than 50 %. A wide range of measures will be required to respond to load variations from wind. This includes heat storages for flexible supply of electricity and heat, electric boilers and heat pumps for use of cheap surplus electricity, electric cars with managed charge of batteries and possible further electric storages, and increased transmission capacity for international trade.

The electricity spot markets, e.g. Nord Pool covering the Nordic countries, are essential for managing electricity loads, when there is a large capacity of wind power. From 2005 a three-level feed-in tariff for decentral CHP was replaced by a premium to the day-ahead, hourly spot market price (13 € per MWh). The day-ahead and intra-day markets is continuously being developed to address the issues of the technology development. From October 2009 a negative minimum price was introduced at the Nord Pool spot market.

Annual aggregated electricity prices from the spot market will be important for future decisions on the investment in CCS facilities.

2.2 Biomass

Wind energy and biomass are the most significant renewable energy sources in Denmark, while the contributions of hydro power, solar and geothermal are negligible.

The total contribution of biomass in 2000 was 70 PJ or 8% of the primary energy requirement. The increase in the use of biomass since 1980 has been a part of the national energy policy. The contribution of biomass has further increased to 100 PJ in 2005.

Incineration of urban waste has a long tradition in the district heating sector, mainly for base-load heat supply, and most urban waste is used for energy.

The use of straw for energy purpose has been developed during the 1990s, mainly with the development of decentralised CHP, and this development has continued after 2000. This includes both combustion facilities for straw at CHP and district heating plants of different sizes as well as the infrastructure for recovery, storage and transport. By 2005 18 PJ or one-third of the available straw resources was used for energy purposes.

Wood chips and wood waste is also used in the district heating sector. Wood pellets have become a convenient replacement of oil for individual boilers, and a significant part of the consumption of wood pellets is imported.

The development of biogas has been much weaker, mainly due to technical and logistical difficulties. In 2005, there was a small production of biodiesel, which was exported.

2.3 Large energy consuming industries

There are very few large energy consuming industries in Denmark that are suitable to consider as explicit technologies in the Pan European model.

There is a single cement plant at Aalborg in North Jutland, located close to the Nordjyllandsværket power station and the potential CO_2 storage at the Vedsted formation.

A steel work using electric arc furnace for melting scraped steel for recycling has worked irregularly for several years with shifting ownership.

The food, chemical and pharmaceutical industries does not contain processes that are identifiable for the Pan European model.

2.4 Industrial CHP

The capacity of Industrial CHP has been gradually increasing over the last decades adding small units. The total capacity has been around 0.6 GW. Generation by industrial autoproducers have been within the range of 2.2 and 3.3. TWh since 2000. The production apparently follows the pattern of the marginal condensing production and the prices on the Nord Pool spot market.

2.5 Refineries

Three refineries were built in Denmark around 1960 and two of them – in Kalundborg and Fredericia – are still in operation. Since the late 1990s the output of oil products from the Danish refineries has been similar to the Danish consumption, except for diesel and residual fuel oil, while Denmark has become a net exporter of crude oil,

3 CCS activities

So far there has been very little interest in CCS in Denmark. The technology is not a part of public policy, and the Government has not expressed any official standpoint on the use of CCS in Denmark. On the other hand, both the electricity industry and geologists from the Geological Survey of Denmark and Greenland (GEUS) have been active in international research on both capture and storage.

Table 3.1. Danish participation in European projects on CCS.

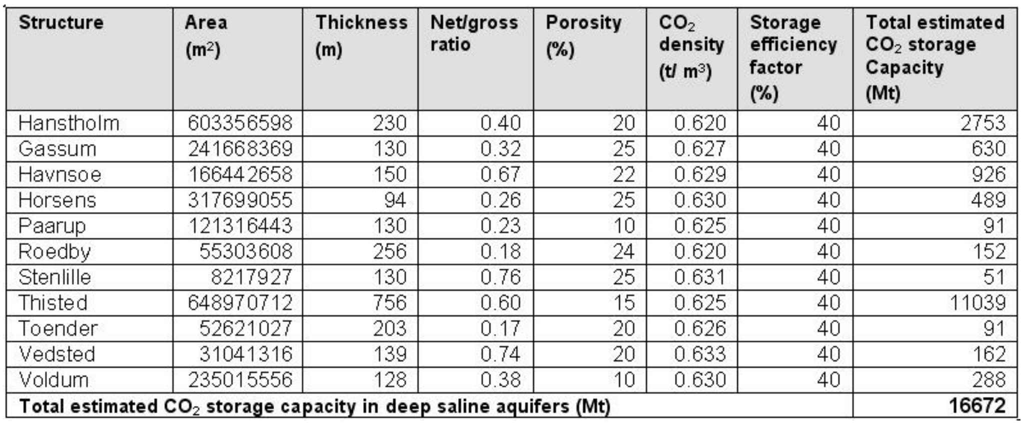
Project	**Participant**	**Contribution**
CASTOR	Geological Survey of Denmark and Greenland (GEUS) Elsam/Energi E2	Test plant at the power plant at Esbjerg
GETSCO	Geological Survey of Denmark and Greenland (GEUS) Danish Oil and Natural Gas (DONG)	GEUS project co-ordinator
GeoCapacity	Geological Survey of Denmark and Greenland (GEUS)	GEUS project co-ordinator

3.1 National storage capacity

The CO_2 storage capacity onshore and near shore in Denmark is very large, some 16,000 mill. ton CO_2, while the offshore capacity in depleted oil and gas fields in the Danish section of the North Sea is much smaller, only 828 mill. ton CO_2. (Oil fields 176 Mt and gas fields 652 Mt)T hese estimates are from the GESTCO project on the European potential for CO_2 storage, which was initiated by GEUS in 1999. GEUS was project leader of both GESTCO (completed in 2003) and the following GeoCapacity project (2002-2006) under the EU 6^{th} Framework Programme with participation from most European countries. The latter project also contains a "conservative estimate of storage capacities, which is much lower. For Denmark this estimate is 2600 mill. ton in Aquifers and 200 mill. ton in hydrocarbon fields (GeoCapacity 2009a, Kober and Blesl, 2010b).

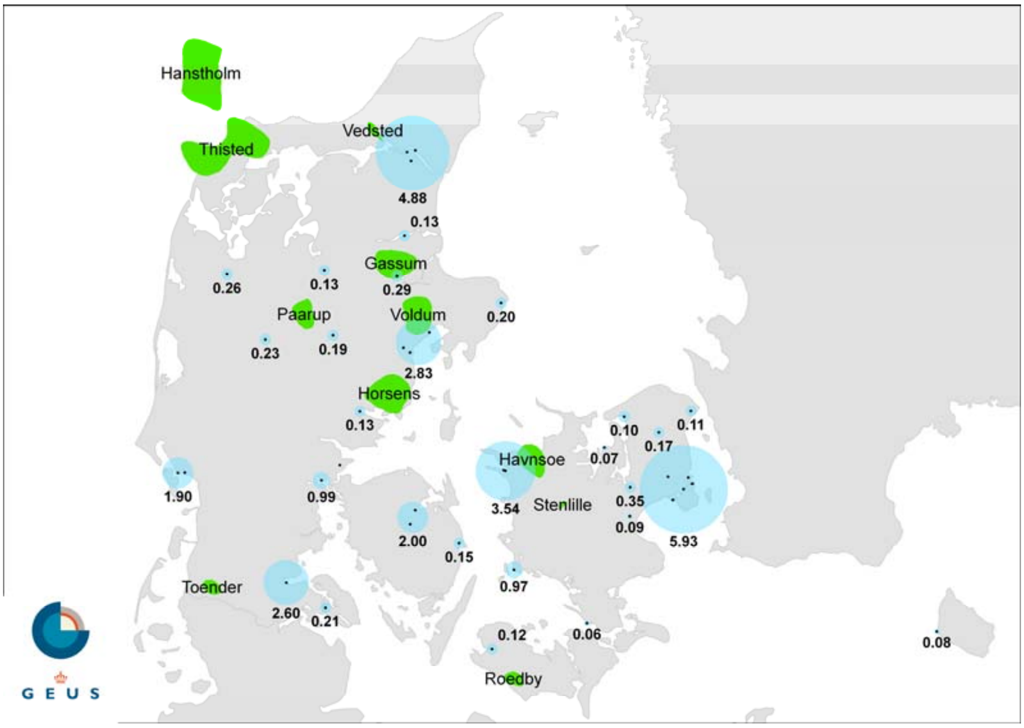
The estimate of the onshore storage capacity was based on a study focusing on 11 individual storage structures mainly in Jutland.

Table 3.2. Main data for 11 identified locations of CO_2 storages in Denmark



Structure	Area (m^2)	Thickness (m)	Net/gross ratio	Porosity (%)	CO_2 density (t/m^3)	Storage efficiency factor (%)	Total estimated CO_2 storage Capacity (Mt)
Hanstholm	603356598	230	0.40	20	0.620	40	2753
Gassum	241668369	130	0.32	25	0.627	40	630
Havnsoe	166442658	150	0.67	22	0.629	40	926
Horsens	317699055	94	0.26	25	0.630	40	489
Paarup	121316443	130	0.23	10	0.625	40	91
Roedby	55303608	256	0.18	24	0.620	40	152
Stenlille	8217927	130	0.76	25	0.631	40	51
Thisted	648970712	756	0.60	15	0.625	40	11039
Toender	52621027	203	0.17	20	0.626	40	91
Vedsted	31041316	139	0.74	20	0.633	40	162
Voldum	235015556	128	0.38	10	0.630	40	288
Total estimated CO_2 storage capacity in deep saline aquifers (Mt)							**16672**

Source: GEUS.



Source: GEUS.

Figure 3.1. Potential CO_2 storages and point sources in Denmark

3.2 Research in CCS

There is a long tradition in Denmark for development and implementation of coal combustion technology for electricity – electricity-only as well as cogeneration with heat. The condensing – electricity-only efficiency of the 300-500 MW extraction-condensing units increased during the last decades from less than 40 % to 47 % at Nordjyllandsværket. The use of seawater cooling instead of cooling towers added some 1.5 %-points to the efficiency. The Danish power companies have played a major role in the AD700[1] project on the development of further efficient coal-fired power stations. Other important technologies have been urban waste incineration and large-scale combustion of straw.

Specifically on carbon capture, DONG Energy has taken part in the CASTOR project, which included a pilot plant at Esbjergværket in Denmark aiming at testing the reliability and efficiency of the post-combustion capture process. The test facility was finished in 2006, and four 1000 hours test campaigns were carried out the following year.

The total CO_2 emission from Denmark in year 2000, which is the starting year of the model study was 52.5 mill ton. Annual variations are significant, because electricity export from coal combustion varies with hydropower production in Norway and Sweden.

3.2.1 CASTOR pilot plant

A test plant was established at the power plant at Esbjerg – owned by DONG Energy within the CASTOR project under the EU 6th Framework Programme in the period 2004-2008. This project was aimed at developing new CO_2 post-combustion separation

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[1] Project supported by the EU, see AD700.dk.The Advanced ("700°C") PF Power Plant project aims at the development of pulverised coal-fired plants with live steam temperatures of 700°C.

processes suited to the problems of capture of CO_2 at low concentrations in large volumes of gases at low pressure. The processes were tested in a pilot unit capable of treating from 1 to 2 tons of CO_2 per hour, from real fumes. At that time it was the largest installation in the world. The pilot plant is a modern CHP coal-fired plant operated by ELSAM (now DONG Energy), which also supplies the district heating system at Esbjerg, located near the Danish North Sea oil and gas fields.

3.2.2 Vedsted formation

In Vedsted, some 30 km from Nordjyllandsværket, Vattenfall started collecting new seismic data in September 2008 as a part of a full-scale project for capture, transport and storage to be available from 2013. The potential CO_2 storage in a geological formation at a depth of 1-2 km under ground[2].

In connection with this, block 3 at the Nordjyllandsværket facility is currently being fitted with a full-scale plant for capturing carbon dioxide using post-combustion technology. However, in the Autumn 2009 it was decided to postpone this project.

3.3 CO_2 transport and storage

The method used for estimating transport cost of CO_2 was developed for the Netherlands (Hoefnagels and Ramirez, 2010) and used by all partners in the Storage Utsira project. The transport cost depends on capacity (scale), distance and terrain factors. The latter encapsulates the geographical and human land use that impact pipeline siting and construction. For example peaty soils, social/legal aspects, dense populated areas and numerous art works and waterways makes on-shore pipeline in the densely populated countries to be expensive.

3.3.1 Model of pipeline costs

To estimate the diameter of the CO_2 pipeline as a function of mass flow, the Ecofys model as presented by McCollum and Ogden (2006) is used (Equation 1). Figure 3.2 presents pipeline diameters as functions of capacity and distance.

$$D = \left(\frac{8 * \lambda * M^2}{\Pi^2 * \rho * \frac{\Delta P}{L}} \right)^{1/5} \qquad \text{eq. 1}$$

D = diameter of the pipeline (m)
λ = friction factor (0.015)
M = mass flow of CO_2 (kg/s)
ρ = CO_2 density (800 kg/M^3)
ΔP = pressure drop ($3*10^6$ Pa)
L = Length pipeline (m)

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[2] From Vattenfall Annual report 2008, http://report.vattenfall.com/annualreport2008/Menu/CCS:

$$I = Ft_{Land\,use} * C * D * L \qquad \text{eq. 2}$$

I = investment cost (€)
$Ft_{Land\ use}$ = terrain factors for different land use types (table x)
C = Constant factor (1600 €/m^2)
D = diameter pipeline (m)
L = length pipeline (m)

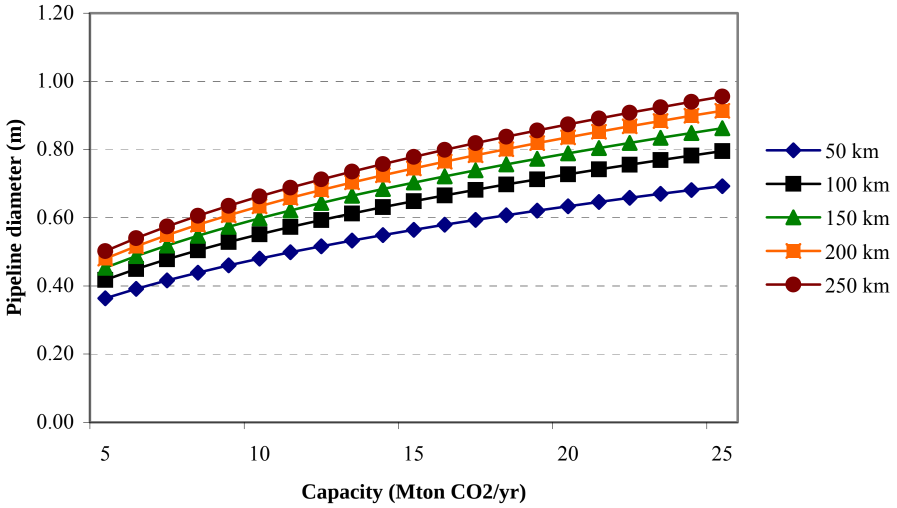

Figure 3.2. Diameter of the pipeline as a function of the CO_2 mass flow.

The investment costs are then calculated using equation 2 (van den Broek et al., 2009). For pipelines longer than 150 to 200 km, a booster station is required to overcome the pressure drop of CO_2 transport. In this study, a booster station is installed for transport distances >150 km to reduce the pressure drop ΔP to 3 MPa (30 bar). The investment costs of the booster station are assumed to be 11 M€, O&M costs are 5% of investment cost and energy cost are 0.11 €/tonne CO_2. (based on an electricity price of € 0.06/kWh and an electricity requirement of 1.9 kWh/tonne CO_2).

Figure 3.3 illustrates CO_2 transport costs by capacity and distance for alternate terrain factors.

A final stage in pipeline cost estimate is via use of a geographical information system (GIS) to derive the optimal configurations of pipeline infrastructures. This step is retained in the Dutch model, and discussed in their national report with respect to fixed integer investments in new capacity. For Denmark cost parameters are calculated in

Table 3.4 for selected maximum flows and distances, which shall represent pipes between different point sources and storage sites.

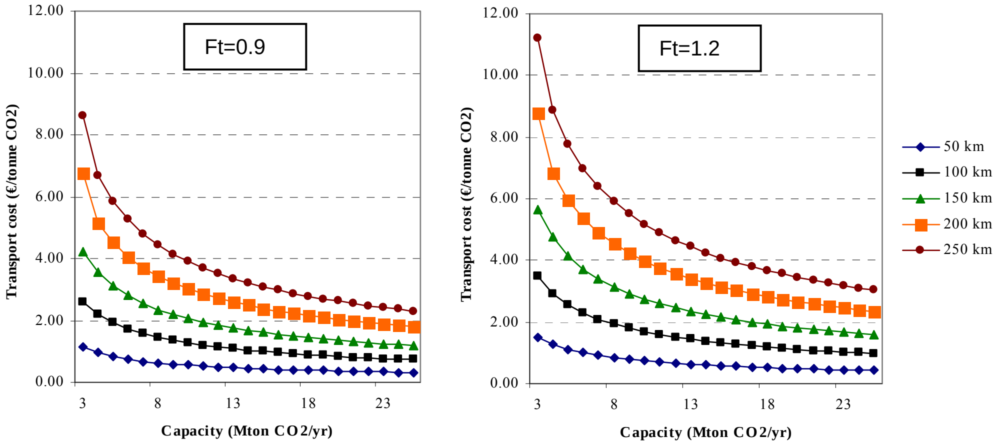

Figure 3.3. CO_2 transportation cost for different capacities, distances and terrain factors.

3.3.2 CO_2 storage costs

A similar analytical process for CO_2 storage has been taken, with engineering derived data aggregated in the UK model, and checked against the detailed reservoir database in the Dutch model. For CO_2 storage quantities, key parameters are the minimum storage size (4 $MtCO_2$ for hydrocarbon fields and 2 $MtCO_2$ for aquifers), the thickness of the reservoir (>10 m), the depth to the top of the reservoir (≥800m), the exclusion of overpressures areas and the seal composition (salt, anhydrite, shale or claystone). For CO_2 storage costs, key parameters are the drilling costs, the site development costs (e.g., exploration costs for aquifer are higher than those of hydrocarbon fields with prior geological data), well fixed costs, and surface facilities (e.g., hydrocarbon fields have old platforms that can be re-used). For Denmark, however, only the standardised cost parameters from the Pan European model are used.

3.3.3 CO_2 transportation costs for Denmark

Table 3.3 shows a set of techno-economic assumptions for the calculation of CO_2 pipeline transportation cost using the Equations 1 and 2 above, and

Table 3.4 shows result for pipeline lengths and CO_2 mass flows that may be used in Denmark for transport of CO_2 between the point sources connected to large and small district heating systems and the domestic onshore and near-shore CO_2 storages. For example 5 Mt mass flow from the power stations in Copenhagen with 100 km to the nearest storage or 250 km to Esbjerg or Hanstholm. Branch pipes from 50-100 MW CCGT units in mid-sized towns are represented by 0.5 Mt mass flow and the distance 50 km. Transport from Danish sources to Utsira is not considered here (see Section 3.5).

As described above, Section 3.1, the main point sources on Zealand are the two large power plants in Copenhagen. The nearest storage possibility is Havnsø, nearly 100 km away. A pipeline should have the dimension 0.42 m and the annual capacity 5 Mt CO_2. Some smaller point sources may be connected to the main pipeline or directly to the storages at Havnsø or Stenlille.

For modelling purpose we can assume 2 pipes of 50 km. However, there is no cost estimate for pipes of smaller dimensions.

Table 3.3. Techno-economic assunptions for CO_2 pipeline and booster station.

Pipeline			
Constant factor	C	1600	€/m2
Discount rate		10%	
Lifetime		40	years
Fixed charge factor (FCF)		10%	
O&M pipeline		2.50%	of capital
Capacity factor		80%	

Friction coefficient	λ	0.015	
CO2 density	ρ	800	kg/m3
Pressure drop	ΔP	3.0E+06	Pa

Booster station		
Investment	11	M€
Fixed O&M	5%	of investment
Electricity price	0.06	€/kWh
Variable O&M	0.114	€/ton CO_2

Table 3.4. Calculation of CO_2 transport cost

Input variables

Mass flow CO2	5	3	5	2	0.5	Mton/yr
Mass flow CO2	159	95	159	63	16	kg CO_2/sec
Length	250	150	100	50	50	km
Booster station	150	150	150	150	150	km
Terrain factor	1	1	1	1	1	

Results

Diameter pipeline	0.50	0.37	0.42	0.25	0.14	m

Investment costs pipeline	201	89	67	20	12	M€
Investment cost booster station	11	11	0	0	0	M€
Fixed O&M cost pipeline	5.02	2.22	1.67	0.50	0.29	M€
Fixed O&M cost booster station	0.55	0.55	0.00	0.00	0.00	M€

Investment cost	5.4	4.2	1.7	1.3	3.0	€/ton CO_2
Fixed O&M	0.1	0.1	0.0	0.0	0.1	€/ton CO_2
Variable O&M	0.1	0.1	0.0	0.0	0.0	€/ton CO_2
Total	5.7	4.5	1.8	1.3	3.0	€/ton CO_2

Table 3.5. Regions for CCS modelling in Denmark

	Source: GEUS Capacity Mt CO2	Annual emissions Mt CO2	Pipeline length Large CHP	Small CHP	No. of units Large CHP	Small CHP	Pipeline capacity 50/100/250 kr Large CHP	Small CHP	Sum	Pipeline dimension Large CHP	Small CHP
Zealand, 100 km	1131	11.59	100	50	1	2	5	3	11	0.42	
Funen, 100 km	0	2.15	100	50	1	3	3		3		
Jutland, 50 km	1463	14.97	50	50	5	3	3	3	24		
Hanstholm/Thisted	13792	0	250	50	1	28	20		20	0.87	
Total	16386	28.71									

Source: GEUS

	Max. Heat, PJ Large CHP	Small CHP	Electricity capacity, GW Central power stations	Waste incineration	Decentral power stations	Total	Heat Capacity, GW District heating boilers	Central power stations	Waste incineration	Decentral power stations	Total
Zealand, 100 km	26.4	6.6	4.71	0.15	0.35	5.20	2.05	4.48	0.67	0.76	7.96
Funen, 100 km	8.3	3.1	0.91	0.07	0.07	1.05	0.77	1.10	0.15	0.16	2.18
Jutland, 50 km	19.4	14.0	3.99	0.19	0.80	4.98	1.90	3.05	0.58	2.09	7.62
Hanstholm/Thisted											
Total	54.0	23.7	9.61	0.41	1.21	11.23	4.72	8.63	1.40	3.00	17.75

Source: Danish Energy Agency. Punktkilder. Download 13-11-2007

3.3.4 Heat recovery by large district heating systems

The models contain techno-economic parameters that quantify expectations on gradually increased efficiencies and lower costs during the next 3-4 decades. The most critical parameter is the loss of thermal efficiency during carbon capture. For example, the efficiency of modern coal-fired steam turbines (pulverised coal) will be reduced from 46 % to 36 %. This will improve in the future for both with and without CCS, and for some of the variants of CCS technologies the difference may be reduced. Table 3.6 shows the assumptions chosen for quantitative modelling in the Storage Utsira project.. This table is based on the assumptions on CCS and reference technologies as shown in Appendix A. For each of the technologies ranges of 5 % above and below the suggested values are shown.

Table 3.6 Efficiencies for new large gas and coal fired power plants and the same technologies with CCS.

		2010	2020	2030	2040
Reference plants	NGCC	58.0	60.0	63.0	64.0
	PC	46.0	50.0	52.0	52.0
	IGCC	46.0	50.0	54.0	56.0
Post combustion, capture rate 85 %	NGCC	49.0	52.0	56.0	58.0
	PC	36.0	42.5	45.0	46.0
Pre combustion, capture rate 85 %	IGCC	38.0	44.0	48.0	50.0
Oxyfuelling plants, capture rate 94 %	NGCC	48.1	50.1	51.6	52.1
	PC	38.0	40.5	43.0	44.0

Although cogeneration technologies for both district heating and industrial processes has been a key issue for The MARKAL and TIMES models, the use of combined heat and power (CHP) has not been systematically studied together with CCS. Obviously some of the energy lost in the carbon capture process could be recovered for heat to supply large-scale district heating systems or industrial processes.

Recent studies by the Dutch partner in the project, Utrecht University has addressed this issue for industrial CHP in different scales, (Kuramochi et al. 2010). The figures for decentralized CHP plants differ substantially from the figures for large scale central generation units (>500 MWe) that are reported in Table 3.6.

For the large scale industrial CHP plants studied in the Netherlands, the energy required for the capture of CO_2 is for a large part used in the form of heat in post-combustion capture systems (mainly for regeneration of solvents). This implies that the total efficiency loss of heat + power is actually higher for CHP plants than for dedicated electricity plants.

Apparently, these results are not valid for Denmark, where large-scale CHP is used exclusively for (mainly large-scale) urban district heating systems. For this type of CHP it has never been studied how much of the lost energy that can be recovered, and the required additional investment in the capture process is unknown, but the additional costs for heat recovery are most likely less than the uncertainty of the investment costs.

Only in few countries the necessary infrastructure is available for a massive use of CCS in combination with CHP. Denmark is the exception, where heat recovery from CCS could have a significant impact within a relatively short time horizon.

This issue is the focus for an abstract “Carbon Capture and Storage: Modelling heat recovery by large district heating systems” submitted to the International Energy Workshop, Stockholm 20-22 June 2010. For this purpose a more specific version of the Pan European TIMES model for Denmark is being developed.

3.4 CCS Policy in Denmark

Until recently, CCS has not been considered as a part of the long-term Danish energy policy. However, in the publication from January 2007 “A visionary Danish energy policy 2025” it was stated: “Trials are at present being made on storing CO_2. If technological development indicates that this can be done cost effectively and without harm to the environment, the consequences for energy policy must be examined in greater detail. Naturally, this still lies some years in the future.”

3.4.1 Phase-out of coal

For more than ten years the government’s official standpoint has been complete phase out of coal rather than support of CCS. In the same period the technology and infrastructure for biomass combustion has been further developed. This includes incineration of nearly all combustible municipal waste in some 30 waste incineration plants supplying base-load heat to the large district heating systems as well as an increasing amount of electricity. In addition straw has become a significant fuel for several small-scale and a few large-scale CHP units. This opens for a vision of negative CO_2 emission, when combining biomass combustion and CCS.

A very significant additional constraint for CCS in Denmark is the planned development of wind power, which currently covers some 20 % of the annual electricity demand, but is planned to increase to more than twice as much. This will further reduce the need for base-load thermal electricity generation

For the model analysis in the Storage Utsira project it means that the potential for CCS is becoming increasingly constrained. To model these constraints, it means that the Pan European TIMES model, which has a structure that is harmonised to meet the requirements for 30 European countries, must be calibrated in further details for give a proper representation of the constrained potential for Denmark.

3.4.2 Official standpoint with respect to CCS

Autumn 2009, the homepage of the Ministry of Climate and energy only contains this short message with reference to Directive 2009/31/EC: “The climate and energy package supports CCS technology, which offers the potential to reduce CO_2 emissions through storage of CO_2 underground” [3]The Danish Energy Agency has a short description of CCS in Danish and a shorter in English, [4]

On the other hand, it is the Government’s long-term vision that Denmark shall become 100 % independent of fossil energy. This may not necessarily include the use of CCS. However, in 2009 the Danish Energy Association published a long-term vision for a future CO_2 neutral energy system in Denmark by 2050, “Power to the people” (Dansk Energi, 2009) This vision is based on three main pillars:

- Energy efficiency
- Renewable energy
- CCS

In the analyses CCS will remove 7.5 Mt CO_2 by 2025 and 17 Mt by 2050. It means that by 2050 CCS should be installed on at least 3000 MW electricity generating capacity (utilisation time 6500 hours/year).

Table 3.7. CO_2 removed by CCS in the scenario from Danish Energy Association, 2009.

	2025	2050
From coal	6.0	7
From biomass	1.5	10
Total	7.5	17

3.5 International network with connection to Utsira

Various scenarios exist with respect to layouts of the pipeline network for these five countries transporting CO_2 streams to the Utsira formation in the North Sea. In this section we classify them into three types and identify their respective features.

Figure 3.4 shows a schematic representation of two of the four network layouts and variants that were considered in WP 5 of this project (Wu and Ramirez, 2010) together with the organisation of investment and operation of the networks. In the first type of network, Network I. In the layout, each country builds and transports CO_2 streams to Utsira through its own pipeline. In the second type of network, Network II, a_2 trunk pipeline towards Utsira or the country is close to storage site (e.g. Norway), the countries might still transport CO_2 directly to Utsira via their own pipelines. Other countries with less mass flows like Denmark, could collaborate and transport CO_2 streams together

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[3] http://kemin.dk/en-US/climateandenergypolicy/EUsclimateandenergypolicy/climateandenergypackage/CCS/Sider/Forside.aspx.

[4] http://www.ens.dk/en-us/policy/eu/climate_energy_package/ccs/sider/forside.aspx.

through a joint trunk. In Network type III a trunk with large transport capacity is constructed from Utsira to the border of Norwegian exclusive economic zone in the North Sea. A sub pipeline is used to bridge CO_2 flows from Norway to this common trunk. The other four countries connect to the transport trunk through constructing individual sub pipelines inside their respective exclusive economic zones as well.

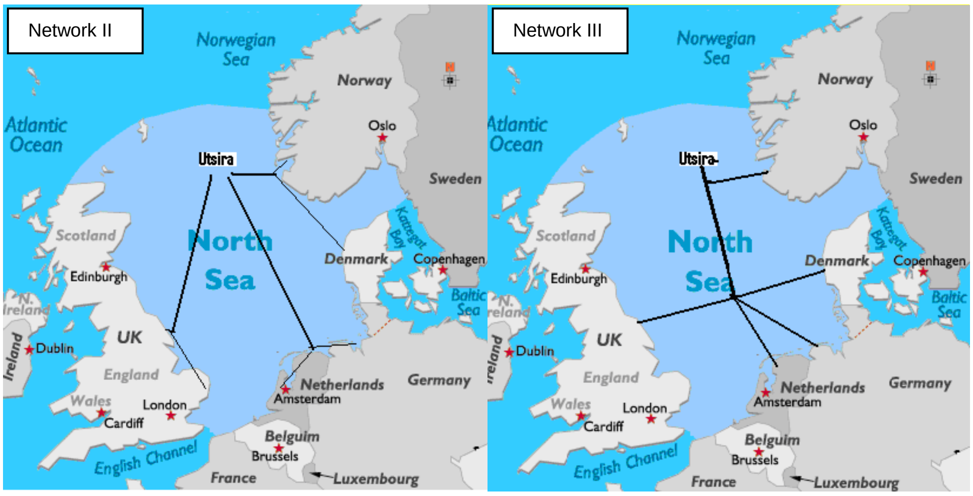

Figure 3.4. Alternative layouts of pipeline network to Utsira

In each of the network layouts there is a connection from Denmark, either from Hanstholm or Esbjerg. In the regional model the Danish hub is called Nybro, which is the location (near Esbjerg) of the gas treatment plant and the landing point for the pipeline from the Danish gas fields in the North Sea. The possibility of a common storage in Denmark, e.g. the large near-shore capacity at Hanstholm in the build-up phase was not considered in WP5.

In Table 3.8 the direct distances from the main power stations to Esbjerg and Hanstholm are shown. From all locations in Jutland (in particular Aarhus, Aalborg, Esbjerg and Skærbækværket) the distance to either Esbjerg or Hanstholm is below 150 km, which does not require a booster station. The distance from the most interesting source location, Copenhagen, is 250-300 km, which will require a booster station.

Table 3.8. Direct distances to Esbjerg and Hanstholm

	Latitude N	Longitude E	Esbjerg	Hanstholn
Esbjerg	55 28	8 27		
Hanstholm	57 06	08 35		
Copenhagen	55 40	12 34	260	292
Århus	56 08	10 11	131	145
Odense	55 24	10 23	122	219
Aalborg	57 02	9 54	196	80
Skærbæk værket	55 31	9 37	74	187
Esbjerg	55 28	8 27	0	182
Kalundborg	55 41	11 06	168	221
Åbenrå	55 03	09 25	77	234
Stignæs værket	55 12	11 15	178	268
Kyndbyværket	55 48	11 52	218	248

3.6 Key assumptions for CCS modelling in Denmark

According to the assumptions made for the Pan European model up to 22 Mt CO_2 per year from Denmark can be transported and stored at costs below 5.5 €/t CO_2, of which hard coal fired power plants represent the major and most reliable emission sources (Figure 3.5). Conversely, the data from industrial installations seems less reliable, which may be due to insufficient or obsolete information in the database used for the model.

Concerning CO_2 storage, low transport costs can be reached, if onshore aquifer storages are available. This seems to be the case for Denmark as shown in Figure 3.6. In contrast to Germany, the Netherlands and the UK Only the cheapest option, “Aquifers onshore” will be needed for storage of the quantities that were identified by the analysis.

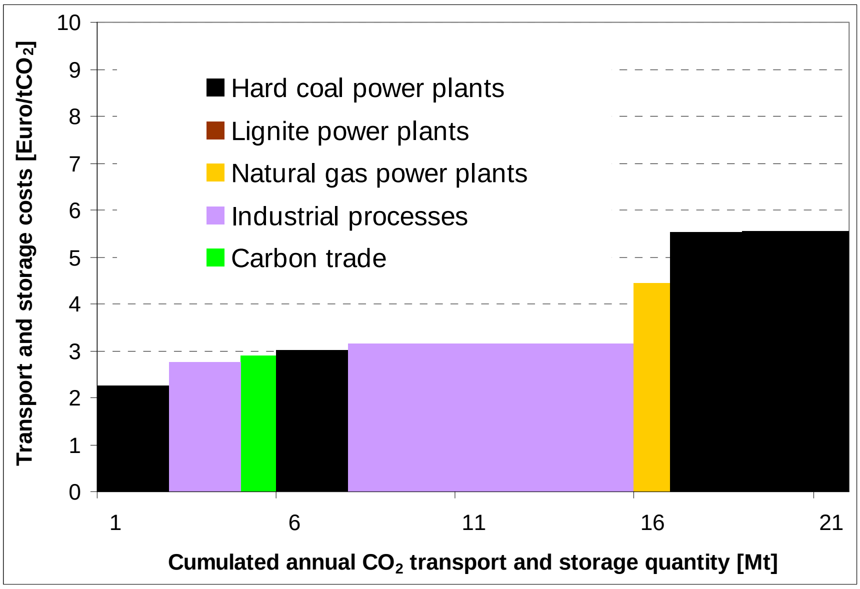

Figure 3.5. Cost potential curve of CO_2 transport and storage in Denmark by emission source

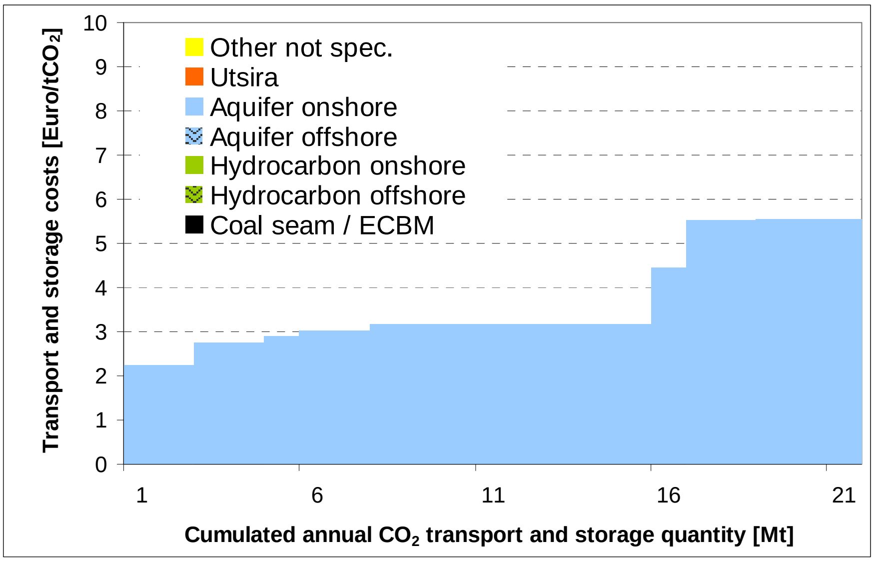

Figure 3.6. Cost potential curve of CO_2 transport and storage in Germany by storage type.

4 Models

The Pan European TIMES model that was developed as a part of the EU research projects NEEDS (www.needs-project.org/) and RES2020 (www.res2020.eu/) now covers more than 30 countries. Model results from studies with time-horizon 2050 will select CCS technologies for most countries, when CO_2 emissions are constrained, but the experience from national model studies is dependent on national priorities.

4.1 Models for the Danish energy sector

From 1988 a more detailed model, RAMSES, was developed within the Danish Energy Agency. RAMSES Version 6 from 2006 is a techno-economic model for electricity and heat in several regions with merit-order optimisation on an hourly basis. Most detailed for West and East Denmark, less detailed for Finland, Sweden and Norway. Investment in new capacity is exogenous. The main output is regional electricity prices, electricity and heat production, fuel requirement fuel and emissions (*www.ens.dk/sw68206.asp* - in Danish).

From 1999 the development of a new optimisation model for analyses of the electricity and CHP sector in the Baltic Sea Region, Balmorel, was developed from scratch. The project was financed by the Danish Energy Research Programme as well as by the institutions from the countries around the Baltic Sea involved in the project. The project succeeded in developing the Balmorel model, and a number of studies were made with it. The model has since then consistently been developed and applied in various contexts, also outside the original focus area. The Balmorel model is coded in GAMS. The Balmorel GAMS code is 'Open Source', which may be downloaded from the project website, *www.balmorel,com* with a complete set of reference data. It may be used and modified following the conditions described on the website.

Balmorel was the starting point for model development under the WILMAR research project supported by the European Commission under the Fifth Framework Programme from 2002 to 2006. The key task of this project was to analyse the integration of wind power in a large liberalised electricity system in Northern Europe, covering four Nordic countries and Germany. Within WILMAR a long-term model was developed to address further integration of wind power in Northern Europe, where some regions are dominated by hydro power production from reservoirs.

None of these models considers the use of CCS in Denmark.

4.2 Pan European TIMES

TIMES is the integrated MARKAL-EFOM system is developed from models used by the IEA (the Implementing Agreement ETSAP) and EU since the mid 1970s. By the end of ETSAP Annex X in 2007 the first scenario results of the Pan-European TIMES model had been presented, as a results of the NEEDS project under the EU 6th Framework Programme.

The further development and application of the Pan-European TIMES model took place under other projects, in particular the RES2020 Project under the EU programme Intelligent Energy Europe. This project was finished Mid-2009, and detailed results have later become available online. Further development are carried out within a number of EU project, e.g. REACCESS, REALISEGRID, PLANETS, plus national and regional applications, including the current Storage Utsira project. The model version developed for PLANETS was used in this project for Germany and Denmark. The following model description is a simplified version of the description of the German national report (Kober and Blasl, 2010b).

The first step for developing the Pan-European model model was the set up of a common Reference Energy System, plus a "SubRES" containing all new technologies that are considered for the model. Demand forecast are made by a set of 'demand drivers', i.e. population, work force, aggregate or sectoral GDP, etc. from economic forecasts.

The model minimizes and objective function equal to the total discounted system cost over the time horizon from 2000 to 2050. A perfect competition among different technologies and paths of energy conversion is assumed in the model. The model covers at the country level, all sectors connected to energy supply and demand, for example the supply of resources, the public and industrial generation of electricity and heat, and the industry, commercial, households and transportation sectors. Both greenhouse gas emissions (CO_2, CH_4, N_2O) and also pollutant emissions (CO, NO_x, SO_2, NMVOC, PM_{10}, $PM_{2.5}$) are modelled.

The generation of electricity and heat in electric power plants, combined heat and power (CHP) plants and heating plants is differentiated into public and industrial production. The model contains three different voltage levels of electricity (high, medium, and low voltages) and two independent heat grids (district heat and local heat).

In the transport sector the four areas (road transport, rail traffic, navigation and aviation) are separately described. Road traffic includes five demand categories for passenger transportation (car short distance, car long distance, bus, coach, motor bikes), and one for freight service (truck). Rail traffic includes the three categories: rail passenger transportation short and long distance, and rail freight transportation. The transport modes navigation and aviation are represented each by a non specified general processes.

The residential sector contains eleven demand categories (space heating, air conditioning, hot water, cooking, lighting, refrigeration, washing machines, laundry dryer, dishwasher, other electrics, other energy use) of which the first three are specified according to building types (single family houses in urban and rural areas and multi-family houses each with stock and new buildings). The commercial sector is represented by a similar reference energy system and consists of nine demand categories (space heating, air conditioning, hot water, cooking, refrigeration, lighting, public street lighting, other electrics, other energy use). The first three of them are subdivided according to different building types (large/small).

The agriculture sector is described by a general process with a mix of several energy carriers as input and an aggregated demand of end use energy as output.

Industry is divided into energy intensive and non intensive branches. While the intensive ones are modelled via a process orientated approach, the other industries have a similar generic structure consisting of five energy services (process heat, steam, machine drive, electrochemical, others). The industrial sector is subdivided into several branches (for example iron and steel, cement, lime, etc.).

In the supply sector all primary energy resources (crude oil, natural gas, hard coal, lignite) are modelled by supply curves with several cost steps. Three categories can be differentiated: discovered reserves (or developed sources), growth of reserves (or secondary and tertiary extraction) and new discoveries. In addition, seven bio energy carriers are defined: mature forest, biogas, household waste, industrial waste, as well as sugary, starchy and lingo-cellulosic crops.

For all regions represented in TIMES PanEU, country specific features, for example different structures of the stock of power plants, different extension potentials for renewables as well as potentials for storing CO_2 are included An interregional electricity trade is implemented in the model, so that exports and imports of electricity according to the existing border capacities are endogenous to the model.

4.3 CCS modelling

The TIMES PanEU model includes different capture technologies of the power generation sector as well as of industrial processes and fuel conversion (Table 4.1).

Table 4.1. CCS technologies in TIMES PanEU

Sector	**CCS-Technology**
Power and heat production	Pre-combustion (hard coal, lignite, gas, wood)
	Post-combustion (hard coal, lignite), also retrofit
	Oxyfuel (hard coal, lignite, gas)
Industry	Iron Blast Furnace with CCS
	Iron Sponge Iron for DRI with CCS
	Advanced Ammonia ProductionCO2 Capture
	Dry Process Cement Production with CO2 capture
Fuel conversion	H2 production coal gasification + PSA + CCS
	H2 production coal gasification + HSMR + CCS

For the aim of this analysis, CCS modelling has to reflect different transport and storage costs for the various emission sources and storages.

The general modelling of the CCS-chain is shown exemplarily at the example of Pulverised Coal Combustion (PCC) with CCS and a representative industrial emission source with CCS and carbon storage using saline aquifers (Figure 4.1). Carbon capture is modelled by process specific parameters of the PCC-CCS and the industry process, which have the commodities “CO_2 captured” and “CO_2 emitted” as output. The share of the two commodities corresponds to the capture rate of the process. The commodity “CO_2 captured” is consumed by the aquifer CO_2 storage processes, which additionally consume the storage specific commodity (“Aquifer storage comm.”). The storage specific commodity (“Aquifer storage comm.”) comes from a process which represents the total, time integral aquifer storage potential. The information of CO_2 transport and storage quantities and costs by storage type and type of emission source, displayed in, Figure 3.5, above.

This approach has been applied to all model regions in TIMES PanEU, which were treated in the GeoCapacity project. Thus TIMES PanEU includes the necessary detailing for the analysis of this project.

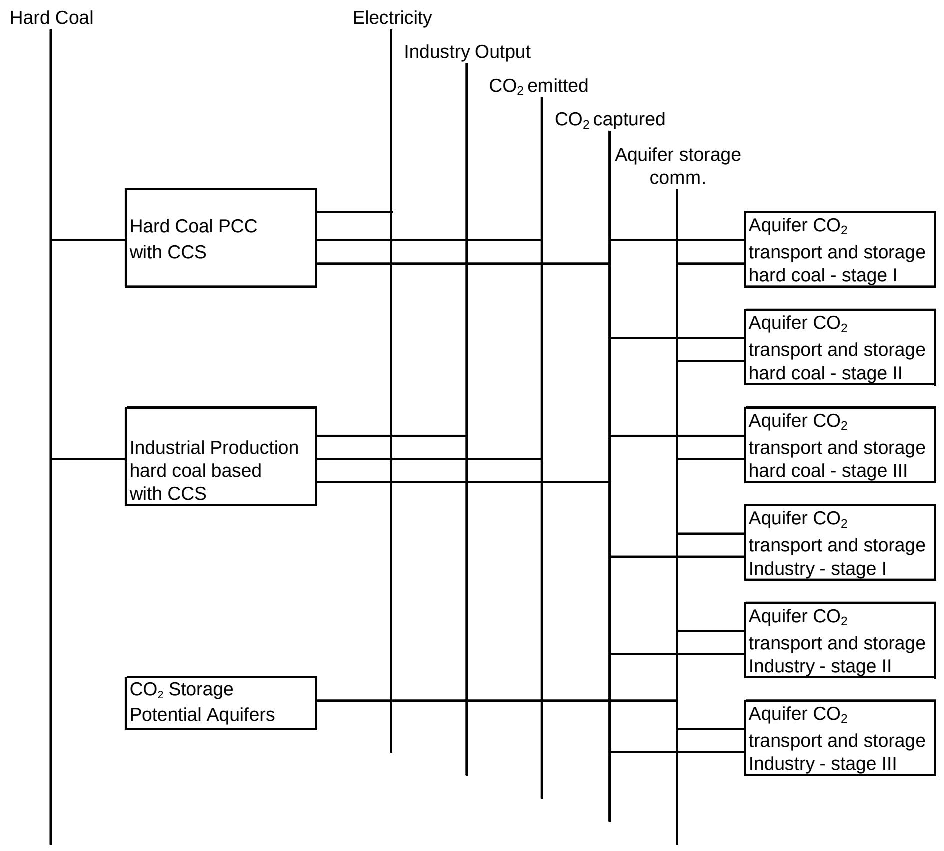

Figure 4.1. CCS modelling in TIMES PanEU – example hard coal fired PCC, industrial production and aquifer CO_2 storage

4.4 Discount rate

For all national and EU regional models in this project, a standard discount rate of 5% was used. This represents a trade-off between a pure social discount rate and a higher commercial rate of return. No technology specific discount or 'hurdle' rates were included. Other applications of the Pan European TIMES model may use a different overall discount rate or technology-specific discount or 'hurdle' rates

5 Results and discussion

So far, there has been no modelling for Denmark focusing on CCS. The detailed models used by the Danish Energy Agency and the electricity and gas system operator, Energinet.dk focus on combined heat, power, and district heating as well as integration of wind power.

This section reports the results for Denmark from four scenarios for EU27 by the Pan European TIMES model developed within the EU FP7 PLANETS until 2050: The four scenarios combines to assumption: Targets for the overall reduction of CO_2 equivalent emissions from EU27 to 20% and 80% and energy prices from the IEA World Energy Outlook 2007 and 2008.

Similar to the earlier versions of the Pan European Model the technology assumptions are standardised and the calibration for the years 2000 and 2005 is based mainly on Eurostat statistic. It means that the calibration does not consider key issues in the structure of the Danish energy systems such as the more detailed structure of district heating and balancing of the large share of wind power.

5.1 Scenario Assumptions

An overview of the characterisation of selected model parameters of TIMES PanEU for Denmark is given in Table 5.1.

Table 5.1. Characterisation of selected model parameters

Parameter	Country: Denmark
Discount rate	• 5 %
Final electricity demand	• Endogenous
Load curve of electricity demand	• Load curve for end uses constant, but if fuel switch of end uses, load curves switches.
Final heat demand (from cogeneration) development	• endogenous with district heating extension potentials • minimum share of heating plants for heat peak load • also onsite cogeneration technologies
Cross-boundary electricity transport	• endogenous
Energy Prices	• WEO 2008 and WEO 2007
Residual capacities of power plants	• Technology specific decommissioning rates. For most technologies: 2000=100, 2005=100, 2010=75, 2015=50, 2020=25, 2025=0.
Policy parameters	• Minimum renewable electricity • Quotas for biofuel use in transport sector

In this study four different scenarios were calculated (Table 5.2). reflecting two climate policy paths, each with high fuel prices (WEO 2008) and lower fuel prices (WEO 2007). For the ambitious climate policy path (GHG-80) a European wide greenhouse gas (GHG) reduction target of 20 % in 2020 increasing to 80 % until 2050 compared to Kyoto base is assumed. Contrary the GHG-20 scenario is less ambitious and states no further GHG reduction requirements for Europe than -20 % in 2020, being constant until 2050.

Table 5.2. Scenario overview

Name	GHG target in 2050	Fuel price	Additional
-80_8	-80 %	WEO 2008	
-20_8	-20 %	WEO 2008	
-80_7	-80 %	WEO 2007	
-20_7	-20 %	WEO 2007	

Since the GHG reduction targets are set for Europe as whole, without predefining national burden sharing, the country allocation of CO_2 emissions differs with varying energy economic conditions, like fuel prices and CCS availability.

5.2 Results from the Pan European model

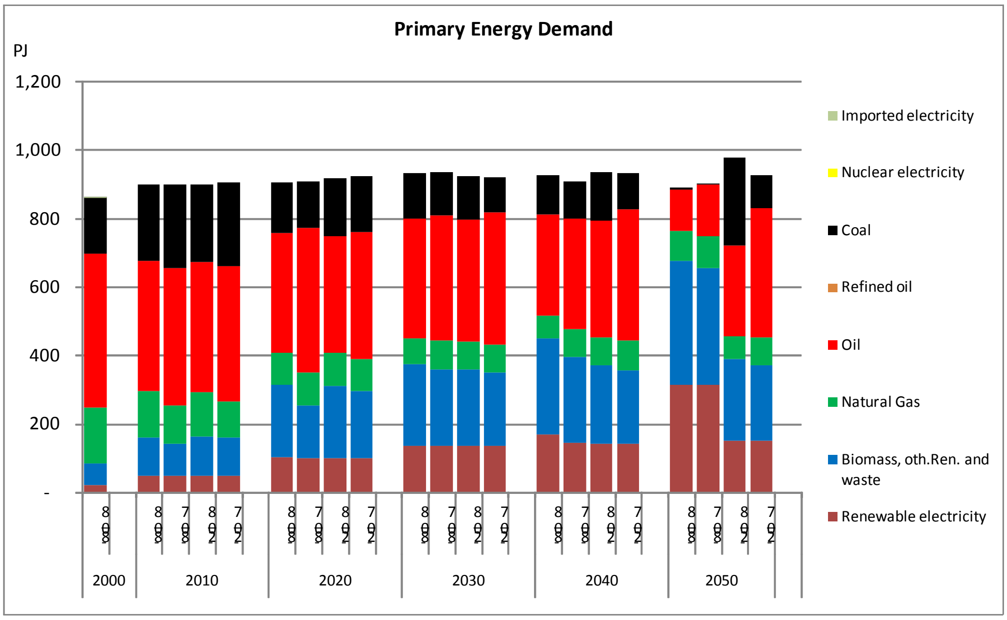

Figure 5.1. Primary energy demand, Denmark, 2000-2050.

The reduction of CO_2 emissions by 20 % for EU 27 as a whole will have fairly little impact of the structure of the Danish energy system after 2020. Electricity demand will increase only modest, by 14% in 2050 compared to 2000 in the case of the WEO 2007 price scenario and 18 % for the WEO 2008 price scenario. The amount of wind power by 2020 will increase beyond the current – very ambitious – national plans, which consider the increase from some 20 % of the domestic demand in 2005-2008 to about 50 % after 2020, which leads to a significant electricity export.

In all scenarios, there is a significant increase in the use of biomass, mainly for electricity and heat. This is broadly in line with national targets. The amount of biomass is best illustrated in Figure 5.1 showing primary energy, while the breakdown of final energy in Figure 5.2 does not represent the Danish energy system very well. The weakest point is the use of biomass for electricity and heat.

The impact of the 80 % reduction of CO_2 emissions will have a far more dramatical impact on the Danish energy system, which is very sensitive to many other assumptions that are not shown in the graphs. Only the impact of the forecasts of fossil fuel prices is refelcted in the graphs.

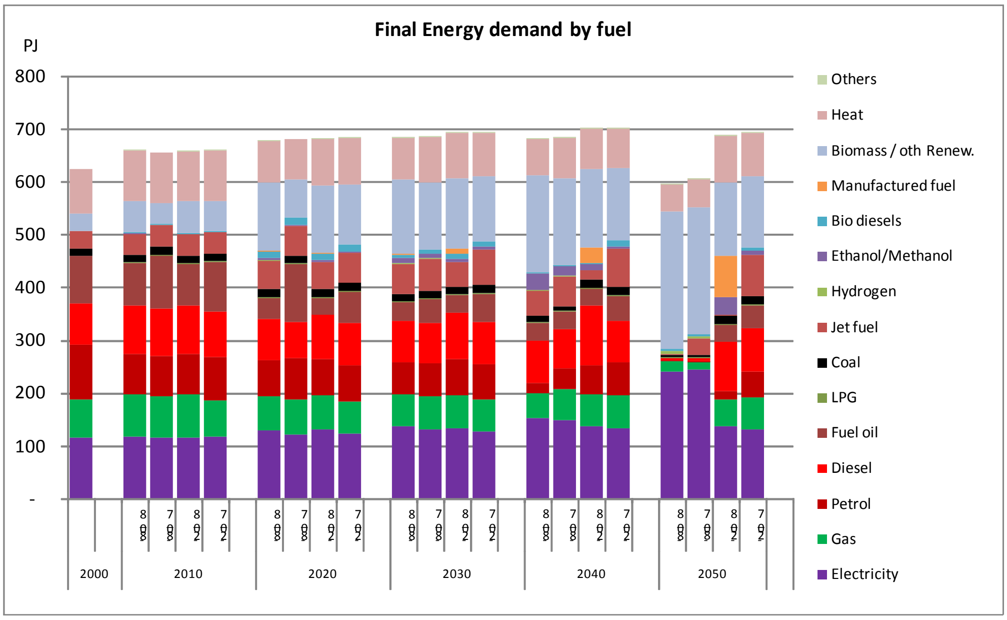

Figure 5.2. Final energy demand by fuel, Denmark, 2000-2050.

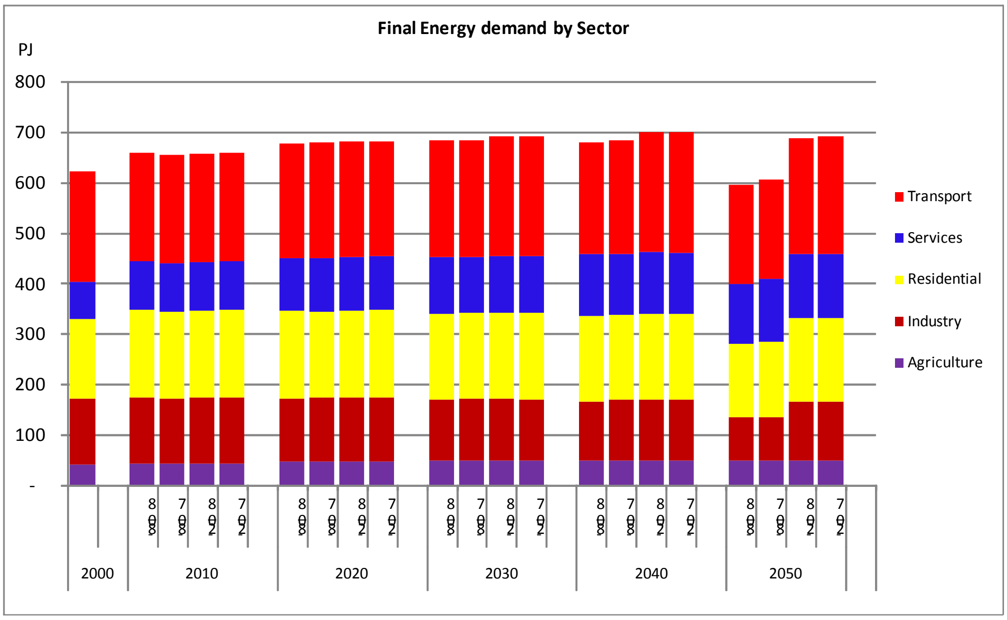

Figure 5.3. Final energy demand by sector, Denmark, 2000-2050

The very dominant feature is the variation of wind power and electricity export. As the offshore potential for wind power from the North Sea and the Baltic Sea is huge, and practically unlimited compared to any forecast of electricity demand in Denmark (European Environment Agency, 2009), model results will be determined of model assumptions outside Denmark. The very large wind capacity in the 80 % reduction cas as shown in Figure 5.6 may be considered as wind capacity located in the Danish part of the North Sea, but serving the German market. A more thorough analysis of these results will require a breakdown into the 12 time-slice used in the model, i.e the four seasons and diurnal demand variations in day, night and peak load – taking into account the limited correllation between the seasonal and diurnal variation of demand and wind production as well as the much stronger element of stochastic variation of wind production.

The very large electricity production by wind leads to a large export of electricity and a shift from oil and gas as final energy to more electricity, in particular in the industrial sector and in transport, see Figure 5.4.

In details these results are very sensitive to the modelling of electricity systems constraints, such as variations of electricity demand over time, and the flexibility of demand and electricity storage capability. The current penetration of wind power is already a challenge for the system, which is handled by the day-ahead electricity spot market and operation of the combined heat and power and district heating systems with teat storages. According to current plans from the electricity system operator this flexibility will be increased over the next decade.

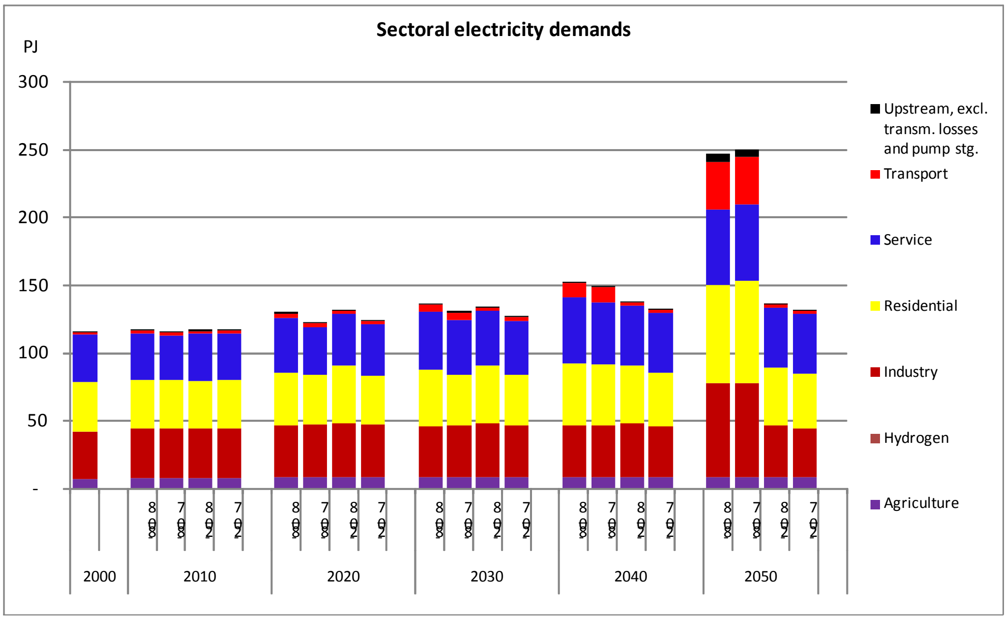

Figure 5.4. Sectoral energy demand, Denmark, 2000-2050

It follows from Figure 5.5 on electricity generation mix that the remaining thermal electricity generation in the 80 % reduction case will be dominated by biomass and coal and gas with CCS. However, the graph, which has the same format for all five countries in this project does not consider biomass CCS, which could be an important technology for Denmark instead of coal or gas CCS. Given the residual character of the thermal generation the model's choice between coal and gas should not be overemphasised.

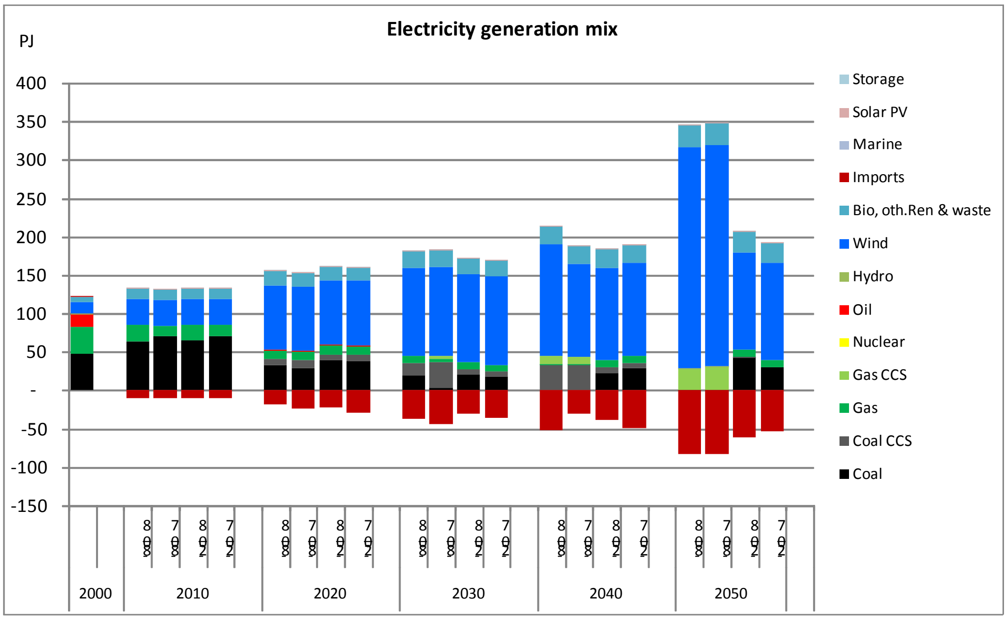

Figure 5.5. Electricity generation mix, Denmark, 2000-2050.

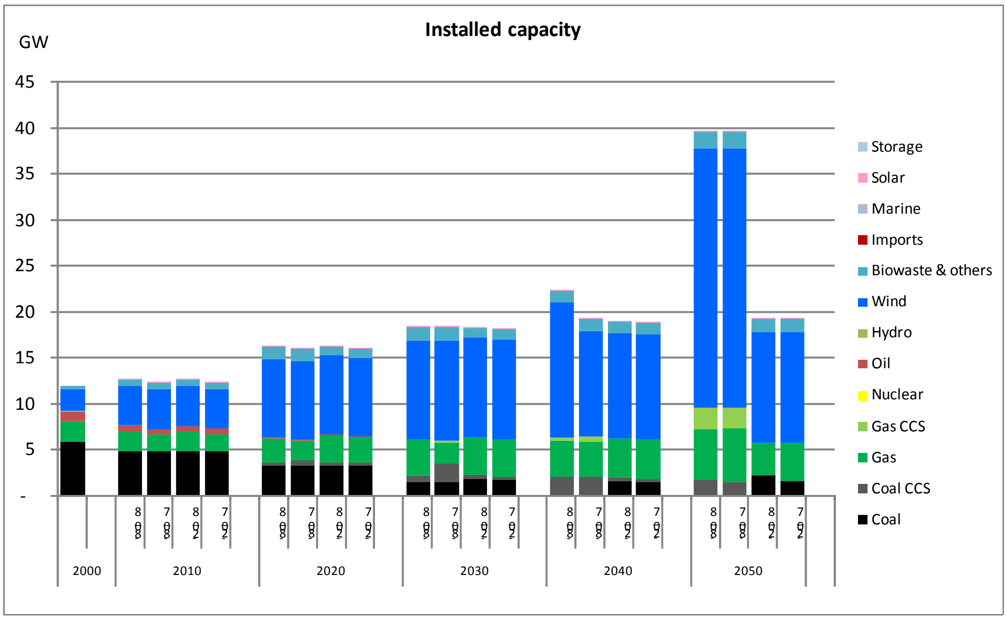

Figure 5.6. Installed capacity, Denmark, 2000-2050

The model does not install electric storages, which could be a major weakness with the large amount of wind power in all scenarios. Heat storages in district heating systems is currently an important feature for dealing with load variations as well as wind power. This is not explicitly shown in the result graphs.

Another important weakness of the model assumptions is that decommissioning of the various technologies is exogenous and dependent on a assumed technical or economic lifetime. Massive integration of wind could be an argument for endogenous lifetime expansion, which will keep a large capacity for reserve and peak load. This is, however, partly seen in the results presented here. The utilisation time for the various technologies shown in Figure 5.5 and Figure 5.6 show 4000-6000 hours for biomass and CCS in 2040 and 2050, some 3000 hours for wind and less than 1000 hours for coal and gas without CCS in some of the scenarios. reserve.

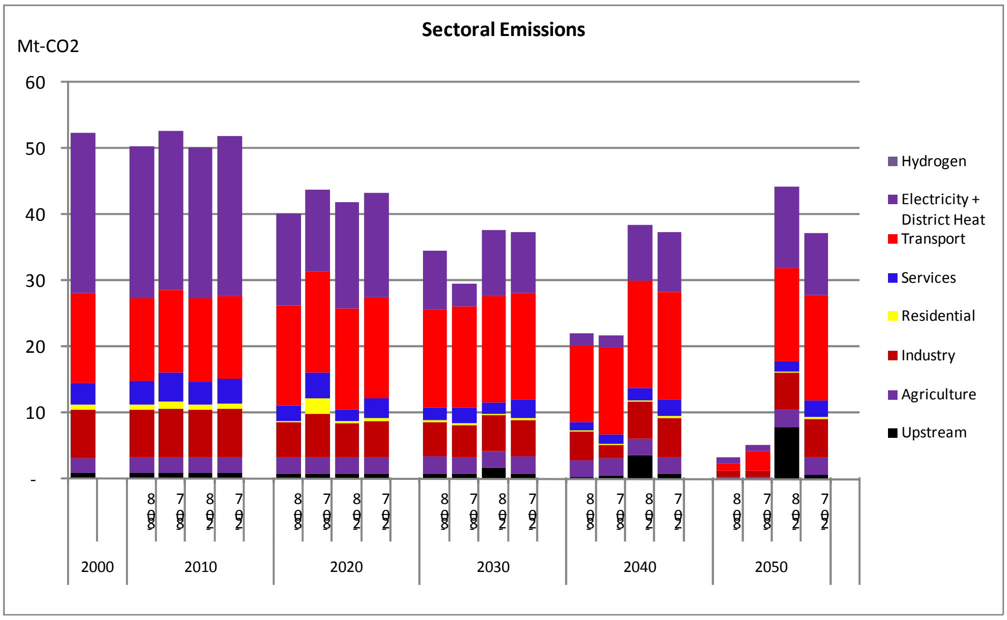

Figure 5.7. Sectoral emissions, Denmark, 2000-2050.

The results for the total and sectoral emissions in Figure 5.7 shows that the reduction in Denmark in the 20% reduction case by 2050 may be lower that EU average depending on price assumptions, while the reduction in the 80 % case will be far beyond the EU average. This is due mainly to the wind resources and the availability of domestic CO_2 storage capacity in domestic onshore and near shore aquifers, as illustrated in Figure 5.8.

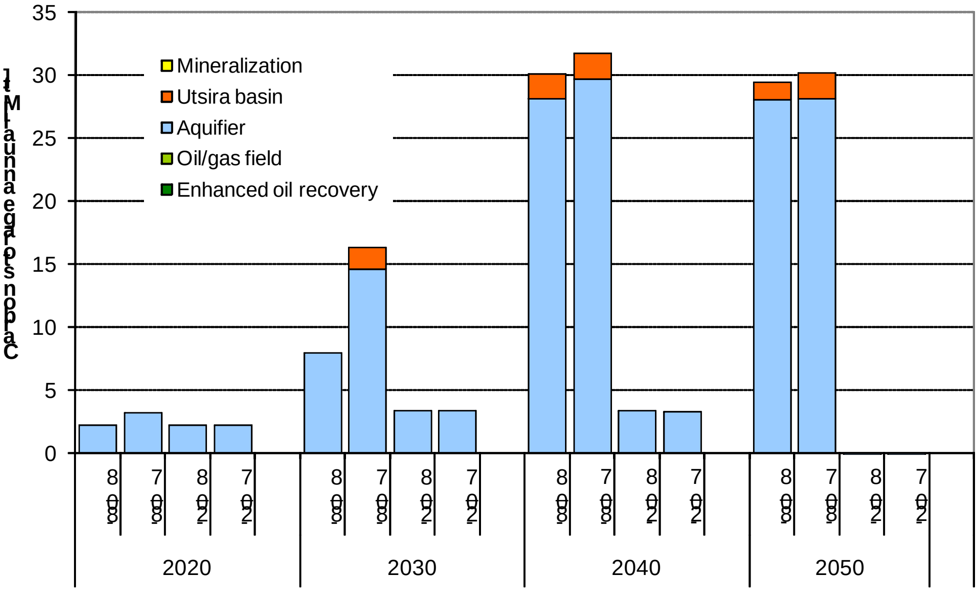

Figure 5.8. Carbon storage, Denmark, 2020-2050

It is notable that enhanced oil recovery and storage in depleted oil and gas fields in the North Sea does not occur in the solution. On the other hand, a small amount of CO_2 will be stored in the Utsira basin. This is merely a result of the infrastructure that is chosen in the multinational model, which includes Denmark in the system of pipelines and possibly will use some of the CO_2 storage capacity in aquifers in Denmark in the built-up phase. Figure 5.8 also shows that the use of the Danish aquifers is highly sensitive to the scenario assumptions. In the 20 % reduction case there is no need for CCS in Denmark

In summary the results for Denmark seems consistent with the assumptions and results for EU27 and (COMPARE_FENCO_EU-27_091217.xls) and for Germany (COMPARE_FENCO_DE_091217.xls), taking into account the energy system structure and resource potential in Denmark. Thus, it presents an international framework for a more detailed modelling for Denmark.

5.3 Results from the DK TIMES model

The DK TIMES model is developed from the NEEDS and RES2020 Pan European model, taking the results until 2025 in the PET-2020_0907 Case as the starting point. All four scenario results from the RES2020 study are available in detail via the RES2020 website, www.res2020.eu. However the full documentation of the VEDA database system and model assumptions allowing the results to be fully reproduced was not yet available at the time of writing (March 2010).

6 Conclusions

The onshore and near-shore CO_2 storage capacity in Denmark is abundant. The electricity system in Denmark is dominated by combined heat and power (CHP) for district heating and wind power. The distance between all urban areas with CHP generation and sufficient CO_2 storage capacity is 50-100 km. The key issues for carbon capture will be heat recovery for district heating combined with biomass combustion. Depleted oil and gas fields in the North Sea and near-shore aquifers may be used for the build up of the international CO_2 transport infrastructure to Utsira.

Reduction of CO_2 emissions by 20 % for EU 27 as a whole will have fairly little impact of the structure of the Danish energy system after 2020. The impact of 80 % reduction of CO_2 emissions will have a far more dramatical impact on the Danish energy system. The very dominant feature is the variation of wind power and electricity import and export. As the offshore potential for wind power from the North Sea and the Baltic Sea is huge, scenario results will be determined of model assumptions outside Denmark.

It is notable that enhanced oil recovery and storage in depleted oil and gas fields in the North Sea does not occur in the solution. On the other hand, a small amount of CO_2 could be stored in the Utsira basin in some years. This is merely a result of the infrastructure that is chosen in the multinational model, which includes Denmark in the system of pipelines, and possibly will use some of the CO_2 storage capacity in aquifers in Denmark in the built-up phase.

The future development of electricity generation in Denmark will be strongly focused on intermittent generation by wind power. This will require international co-operation on international markets and transmission lines. In addition, a large thermal capacity is needed in periods with little wind. Coal or biomass fired CHP with CCS is an options that offers efficient electricity generation with no – or even negative – CO_2 emissions.

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Appendix A. PET model input and results

Overview of harmonised power plant parameters (source: Hoefnagels and Ramirez, 2010)

Table A. 1. NGCC technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	676	608	608	608
	Range	499 - 780	499 - 741	423 - 696	499 - 608
Fixed O&M (€/kW-yr)	Default	19	17	16	16
	Range	10 - 25	9 - 24	9 - 24	12 - 24
Variable O&M (€/GJ)	Default	0.02	0.02	0.02	0.02
	Range	0.02 - 1.08	0.02 - 1.08	0.02 - 1.08	0.02 - 0.57
Efficiency (% LHV)	Default	58	60	63	64
	Range	57.0 - 61.1	57.4 - 63.9	57.4 - 68.1	57.4 - 64.0

Table A. 2. PC technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	1598	1487	1448	1352
	Range	1071 - 1692	977 - 1487	889 - 1538	1127 - 1352
Fixed O&M (€/kW-yr)	Default	77	72	66	61
	Range	24 77	24 72	24 66	45 61
Variable O&M (€/GJ)	Default	0.36	0.35	0.33	0.33
	Range	0.36 - 0.95	0.35 - 0.95	0.33 - 0.95	0.33 - 0.95
Efficiency (% LHV)	Default	46	50	52	52
	Range	45.0 - 47.0	49.0 - 50.0	52.0 - 54.2	52.0 - 53.0

Table A. 3. IGCC technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	2005	1798	1691	1521
	Range	1230 - 2005	1207 - 1798	1000 - 1691	1466 - 1521
Fixed O&M (€/kW-yr)	Default	71	66	60	53
	Range	27 71	27 70	27 70	53 70
Variable O&M (€/GJ)	Default	0.29	0.25	0.20	0.19
	Range	0.29 - 1.14	0.25 - 1.14	0.20 - 1.14	0.19 - 1.14
Efficiency (% LHV)	Default	46	50	54	56
	Range	43.9 - 46.0	45.4 - 52.0	46.9 - 54.5	54.5 - 56.0

Table A. 4. NGCC CCS (post) technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	1146	1014	938	838
	Range	769 - 1733	837 - 1466	615 - 1233	648 - 1233
Fixed O&M (€/kW-yr)	Default	71	66	60	53
	Range	17 - 71	17 - 70	17 - 70	17 - 70
Variable O&M (€/GJ)	Default	0.41	0.40	0.36	0.35
	Range	0.41 - 0.92	0.40 - 0.99	0.36 - 1.09	0.35 - 1.09
Efficiency (% LHV)	Default	49	52	56	58
	Range	49.0 - 56.0	49.0 - 56.6	49.0 - 61.8	49.0 - 67.1
Capture rate (%)	Default	85	85	85	85
	Range	85 - 90	85 - 90	85 - 90	85 - 90

Table A. 5. PC CCS (post) technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	2546	2328	2110	1892
	Range	1355 - 2546	1166 - 2700	1123 - 2110	1892 - 1920
Fixed O&M (€/kW-yr)	Default	95	81	75	68
	Range	36 98	36 81	36 - 77	56 - 68
Variable O&M (€/GJ)	Default	1.29	1.25	1.08	0.95
	Range	1.05 - 1.46	1.00 - 2.00	1.05 - 1.46	0.95 - 1.10
Efficiency (% LHV)	Default	36	42.5	45	46
	Range	36.0 40.0	40.0 42.5	44.0 47.3	46.0 47.0
Capture rate (%)	Default	85	85	85	85
	Range	85 - 90	88 - 90	85 - 90	85 - 90

Table A. 6. IGCC CCS (post) technology comparison.

Year		2010	2020	2030	2040
Capital (€/kW)	Default	2769	2374	2130	1956
	Range	1694 - 2769	1540 - 2374	1322 - 2130	1826 - 1956
Fixed O&M (€/kW-yr)	Default	92	76	70	63
	Range	36 - 92	36 - 87	36 - 87	63 - 87
Variable O&M (€/GJ)	Default	0.51	0.41	0.27	0.27
	Range	0.51 - 1.41	0.41 1.41	0.27 - 1.41	0.27 - 1.33
Efficiency (% LHV)	Default	38	44	48	50
	Range	35.0 - 46.0	40.4 - 46.0	41.9 - 48.5	48.5 - 50.0
Capture rate (%)	Default	85	85	85	85
	Range	85 - 90	88 - 90	85 - 90	88 - 90

Table A. 7.Results of Pan European TIMES for Denmark I

Primary Energy Demand (PJ)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
	-80_8	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Renewable electricity	21	48	48	47	47	101	101	100	100	136	136	135	135	168	144	143	143	316	316	152	152
Biomass, oth.Ren. and waste	65	114	95	116	113	214	154	212	197	239	223	225	216	282	251	229	215	360	341	237	219
Natural Gas	164	133	111	130	104	94	95	95	91	76	85	83	82	66	81	81	87	88	92	68	82
Oil	448	382	403	382	398	350	423	343	373	351	367	356	387	298	324	341	384	122	151	264	379
Refined oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	167	223	244	224	244	147	138	169	164	131	125	125	101	115	109	144	106	5	4	259	95
Nuclear electricity	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Imported electricity	2	-10	-10	-10	-10	-18	-23	-22	-29	-36	-44	-30	-35	-51	-30	-38	-49	-82	-82	-61	-53
Hydrogen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	865	889	891	889	897	888	888	902	898	897	892	908	886	878	879	944	885	809	822	978	874

Final Energy demand by fuel (PJ)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Electricity	115	116	115	116	117	129	122	131	124	136	130	134	126	152	149	137	132	241	245	137	132
Fuel oil	91	81	101	80	95	41	109	32	60	36	46	33	54	33	33	33	46	3	3	33	44
LPG	-	1	1	1	1	1	1	1	1	2	2	2	2	1	2	2	2	0	0	0	2
Gas	72	82	78	82	69	64	65	64	60	61	63	62	62	48	59	60	64	18	14	50	59
Coal	13	14	14	14	14	15	15	15	15	14	13	15	15	13	7	15	15	3	3	16	16
Petrol	105	76	76	76	82	69	78	68	69	60	63	67	67	19	39	56	62	1	1	16	49
Diesel	78	91	91	91	86	78	69	85	80	78	76	89	80	80	74	113	79	5	5	94	83
Jet fuel	34	42	42	41	42	55	56	52	56	58	61	48	66	48	58	18	73	3	32	3	77
Hydrogen	-	-	-	-	-	0	-	-	-	0	0	-	-	1	1	-	-	4	4	-	-
Ethanol/Methanol	-	0	-	-	-	4	2	3	3	11	8	5	7	30	20	12	3	-	-	32	8
Bio diesels	-	1	1	1	1	13	14	13	13	6	8	10	10	2	0	1	12	5	4	-	7
Manufactured fuel	-	-	-	-	-	1	-	1	-	1	-	10	-	-	-	30	-	-	-	78	-
Biomass / oth Renew.	31	59	40	59	58	128	71	127	113	141	127	132	122	184	165	148	136	259	241	139	134
Heat	85	97	97	95	96	81	76	89	88	81	87	87	84	70	77	77	77	53	55	90	83
Others	-	1	-	1	1	1	-	1	1	0	1	0	0	0	0	0	0	0	0	0	0
Total	624	660	656	659	661	680	680	683	684	685	686	694	693	682	684	701	702	596	607	688	694

Final Energy demand by Sector (PJ)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Agriculture	41	44	44	44	44	47	47	47	47	49	49	49	49	49	49	49	49	49	49	49	49
Industry	131	130	129	130	131	126	127	127	128	122	123	123	122	117	120	122	121	87	87	117	117
Residential	159	174	172	172	173	173	171	173	173	171	171	171	171	170	169	169	169	146	149	166	167
Services	74	97	95	97	97	105	106	106	107	111	110	113	113	123	122	123	123	118	125	127	127
Transport	219	216	216	216	216	228	229	229	229	233	233	238	238	222	224	238	240	196	195	230	234
Total	624	660	656	659	661	680	680	683	684	685	686	694	693	682	684	701	702	596	607	688	694

Table A. 8.Results of Pan European TIMES for Denmark II

Electricity generation mix (PJ)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Coal	47	64	71	65	71	33	29	39	39	20	3	21	18	-	-	23	28	-	-	43	30
Coal CCS	-	-	-	-	-	7	10	7	7	16	33	7	7	34	34	7	7.04	1	0	0	-
Gas	35	21	14	20	15	13	12	13	13	9	5	9	9	0	0	9	10	0	0	10	10
Gas CCS	-	-	-	-	-	-	-	-	-	-	4	-	-	10	9	-	-	28	31	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oil	18	-	-	-	-	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
Hydro	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-
Wind	15	34	34	34	34	84	84	84	84	115	115	115	115	145	121	121	121	288	288	126	126
Bio, oth.Ren & waste	6	15	15	15	15	19	18	19	19	23	22	22	22	25	25	24	24	30	30	27	27
Imports	2	- 10	- 10	- 10	- 10	- 18	- 23	- 22	- 29	- 36	- 44	- 30	- 35	- 51	- 30	- 38	- 49	- 82	- 82	- 61	- 53
Marine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Solar PV	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	123	123	122	123	124	138	131	140	132	146	139	143	135	163	159	146	141	264	267	146	140

Installed capacity by fuel (GW)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Coal	6	5	5	5	5	3	3	3	3	1	1	2	2	-	-	2	1	-	-	2	2
Coal CCS	0.00	0.00	0.00	0.00	0.00	0.35	0.56	0.35	0.35	0.74	2.00	0.35	0.35	2.03	2.00	0.35	0.35	1.68	1.44	0.00	0.00
Gas	2	2	2	2	2	3	2	3	3	4	2	4	4	4	4	4	4	6	6	3	4
Gas CCS	-	-	-	-	-	-	-	-	-	-	0	-	-	0	1	-	-	2	2	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oil	1	1	1	1	1	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
Hydro	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	-	-
Wind	2	4	4	4	4	9	9	9	9	11	11	11	11	15	11	11	11	28	28	12	12
Biowaste & others	0	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	2	2	1	1
Imports	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Marine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Solar	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	12	13	12	13	12	16	16	16	16	18	18	18	18	22	19	19	19	40	40	19	19

Sectoral electricity demands (PJ)	**2000**	**2010**				**2020**				**2030**				**2040**				**2050**			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Agriculture	7	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Hydrogen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industry	35	37	37	37	37	39	39	40	39	38	38	40	38	38	38	39	37	69	69	38	36
Residential	36	35	35	35	35	38	37	43	37	41	38	43	37	46	46	43	39	72	76	43	40
Service	36	35	33	35	35	41	35	38	38	43	40	40	40	49	46	44	44	56	56	44	44
Transport	1	2	2	2	2	3	3	2	2	6	6	3	3	11	11	3	3	35	35	3	3
Upstream, excl. transm. losses and pump stg.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	6	5	0	1
Total	116	117	116	117	118	130	123	132	125	137	131	135	127	152	149	138	133	247	250	137	132

Table A. 9.Results of Pan European TIMES for Denmark III

Sectoral Emissions (Million t-CO2)	2000	2010				2020				2030				2040				2050			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Upstream	1	1	1	1	1	1	1	1	1	1	1	2	1	0	0	4	1	-	-	8	1
Agriculture	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	0	0	3	3
Electricity + District Heat	24	23	24	23	24	14	12	16	16	9	4	10	9	2	2	9	9	1	1	12	9
Hydrogen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industry	7	7	7	7	7	5	7	5	5	5	5	5	5	4	2	6	6	1	1	6	6
Residential	1	1	1	1	1	0	2	0	0	0	0	0	0	0	0	0	0	-	-	0	0
Services	3	4	4	3	4	2	4	2	3	2	2	2	3	1	1	2	3	-	-	1	2
Transport	14	13	13	13	13	15	15	15	15	15	15	16	16	12	13	16	16	1	3	14	16
Total	52	50	53	50	52	40	44	42	43	35	30	39	37	22	22	44	37	3	5	52	37

CO2 and system costs	2000	2010				2020				2030				2040				2050			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
CO2 emissions (MTCO2)	52.3	50.3	52.6	50.2	51.8	40.1	43.7	42.3	43.3	34.5	29.5	39.5	37.3	22.0	21.8	44.1	37.3	3.3	5.2	51.7	37.1
Marginal cost of CO2 (€2000/t)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Undiscounted energy system cost (€ billion)	43	17	17	17	17	22	20	22	20	26	24	26	23	21	19	21	19	21	21	21	19
Discounted energy system cost (€ Billion)	43	12	11	12	11	10	9	10	9	8	7	8	7	4	4	4	4	3	3	3	3

Transport fuel demand	2000	2010				2020				2030				2040				2050			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
Petrol	105	76	76	76	82	69	78	68	69	60	63	67	67	19	39	56	62	1	1	16	49
Diesel, FT-fossil	79	93	92	93	88	81	71	86	82	81	78	91	82	82	76	115	81	7	7	96	85
Electricity	1	2	2	2	2	3	3	2	2	6	6	3	3	11	11	3	3	35	35	3	3
Hydrogen	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	4	4	0	0
Jet fuel	34	42	42	41	42	55	56	52	56	58	61	48	66	48	58	18	73	3	32	3	77
Bio-diesel, FT-bio	0	1	1	2	1	13	14	13	13	12	12	10	10	27	15	1	12	137	113	0	7
Ethanol/methanol	0	0	0	0	0	4	2	3	3	11	8	5	7	30	20	12	3	0	0	32	8
Gaseous Fuels	0	2	2	2	2	3	3	4	3	4	4	14	4	3	4	35	5	7	3	80	6
Total	219	216	216	216	216	228	229	229	229	233	233	238	238	222	224	238	240	196	195	230	234

CCS (MtCO2)	2000	2010				2020				2030				2040				2050			
		-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7	-80_8	-80_7	-20_8	-20_7
All CCS	0.0	0.0	0.0	0.0	0.0	1.3	2.2	1.3	1.3	3.6	9.8	1.3	1.3	10.1	12.8	1.3	1.3	9.4	10.2	0.0	0.0
CCS electricity	0.0	0.0	0.0	0.0	0.0	1.3	2.2	1.3	1.3	3.5	9.2	1.3	1.3	9.3	10.5	1.3	1.3	7.0	7.7	0.0	0.0
CCS process/Industry	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.9	2.4	0.0	0.0	2.4	2.4	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Enhanced oil recovery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil/gas field	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil/gas field - high transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aquifier	0.0	0.0	0.0	0.0	0.0	2.2	3.2	2.3	2.3	8.0	14.6	3.4	3.4	28.1	29.7	3.4	3.3	28.0	28.2	0.0	0.0
Utsira basin	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	2.0	2.0	0.0	0.0	1.4	2.0	0.0	0.0
Mineralization	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0