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Structural change of the economy, technological progress and long-term energy demand

Klinge Jacobsen, Henrik

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Henrik Klinge Jacobsen

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Contents

Preface

This report is a result of a project carried out in the period from August 1996 to September 1999 and financed by the Danish Energy Research Programme (EFP) 1996. The project has been carried out as a PhD project, and the material included in the report is a collection of papers dealing with different issues related to the topics included in the title. Some of these papers have already either been published or presented at various conferences. Together with a general introduction, they constitute the author's PhD dissertation. The dissertation includes six papers and two shorter notes on different aspects of structural change of the economy and energy demand. Three different issues related to long-term energy demand are discussed: (1) the importance of technological change and its representation in energy-economy modelling, (2) an integration of two different modelling approaches, and (3) the effect on energy demand of structural changes exemplified by changes in the energy supply sector and in Danish trade patterns.

The report highlights a few aspects of the interaction between structural economic changes and energy demand, but it does not intend to cover a wide range of issues related to these topics. In the introductory chapter some discussions and thoughts about issues not covered by the articles are brought forward.

The introductory chapter includes an overview of possible relations between long-term energy demand and the economy, technical progress, demography, social conditions and politics.

The first two papers discuss the importance for projections of long-term energy demand of the way in which technological progress is modelled. These papers focus on energy-economy modelling.

A paper dealing with two different approaches to energy demand modelling and the possible integration of these approaches in the Danish case follows next. The integrated Danish model, is then used for analysing different revenue recycling principles in relation to a CO_2 tax. The effect of subsidising biomass use is compared with recycling through corporate tax rates.

Then a paper follows describing the structural change of a specific sector, namely the energy supply sector, and the implications for long-term energy demand. The last two papers are devoted to the structural change of trade patterns and its implications for long-term energy demand from industries and the effects on trade from changes in energy technology.

Finally, an extended paper document the model applied for the analyses in paper three to paper five in combination with a critical assessment of the model and the results obtained in the first five papers. The last section of this paper is devoted to a summary of conclusions and suggestions for future research.

I want to thank a number of my colleagues at Risø, who have contributed with valuable comments and suggestions. I also want to thank my PhD supervisor Jørgen Birk Mortensen for his continued support of the project.

General introduction

1. Long-term energy demand

The theme of this study is long-term energy demand and its link with technological progress and structural changes in the economy. It is obvious that the expression "long-term" can be used in a number of meanings. Here the term will mean something between 10 and 100 years. It will be examined whether certain explanatory factors for long-term energy demand become more, or less, important when the horizon is expanded.

The long-term energy demand can be important for a number of very different reasons. Longterm energy demand is important for planning of the energy supply system. Energy and environmental targeting along with international commitments makes the understanding of the driving factors for long-term demand an important issue if some appropriate policies should be designed. Also, the actors in the markets for different fuels and other energy will be sensitive to long-term trends.

Energy as an input to production is a basic input and is needed to secure both the present material living standard of the society and a possible growth in future consumption opportunities. At the same time energy, in both the supply and demand sectors, is one of the main contributors to GHG (greenhouse gas) emissions, acid rain and other kinds of urban pollution. This is the reason for the focus on a possible trade-off between environmental quality and economic growth. Much of the research in the field of long-term energy issues is initiated by the concern for moderating this trade-off.

In the general introduction, focus is placed on the Danish developments and an overview of different factors related to long-term energy demand in Denmark.

2. What has been the picture of long-term energy demand in Denmark?

Long-term energy demand in Denmark has been rising at an average of 2.9% a year from 1900 to 1997[1]. During the last quarter of this century the growth has been much slower. Primary energy consumption almost remained unchanged from 1972-1997, with an annual growth of only 0.1%. The change in the structure of the economy from manufacturing and agriculture towards a more service orientation, and especially a widened public sector, has influenced energy demand development. The slow growth of energy demand in the last 25 years has been accomplished by a sharp rise in energy prices, especially for private consumers, and a remarkable effort from energy planning authorities and the restructuring of residential energy supplies for heating. The structural changes in the economy with a larger production share of the service service have reduced the options for further reductions in average energy intensity in production. Furthermore, the potential for improving energy efficiency in residential energy consumption is also limited. Therefore, the structural change of the economy is an important issue influencing both energy demand and the available policy options for the authorities.

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[1] For the data from 1900-1958 the source is Energy Supply of Denmark 1900-1958, Statistiske Undersøgelser nr. 2, København 1959.

The price of energy has varied a great deal in the period, both totally and among the individual energy supplies. Bentzen (1993b) calculated a real consumer price for residential energy consumption for the period 1900-1991. This series shows large fluctuations with an increase in real energy price over this period of around 30%. The increase in real energy price, since the level prevailing in the fifties and sixties to 1991 has been around 100%. If instead, the real energy prices for production input were examined (Thomsen 1993, fig 10.) the real price would be unchanged from 1948 to 1989 with even larger fluctuations than for consumer price; around 25% lower in the sixties and 75% higher in the beginning of the eighties.

Figure 1 shows the development and composition of primary energy demand in the period 1975-1997. Total primary energy consumption is stable, but the composition of fuels has changed from what it was in an almost entirely oil-dependent economy to a situation where the fuels are much more diversified in their use. The reduction in total energy consumption following the second oil crisis is accompanied by a switch from an oil-based to a primarily coal-based power production. This structural change can be observed in combination with the introduction of a new fuel, namely natural gas, which constitutes another infrastructure and public planning-related structural change.

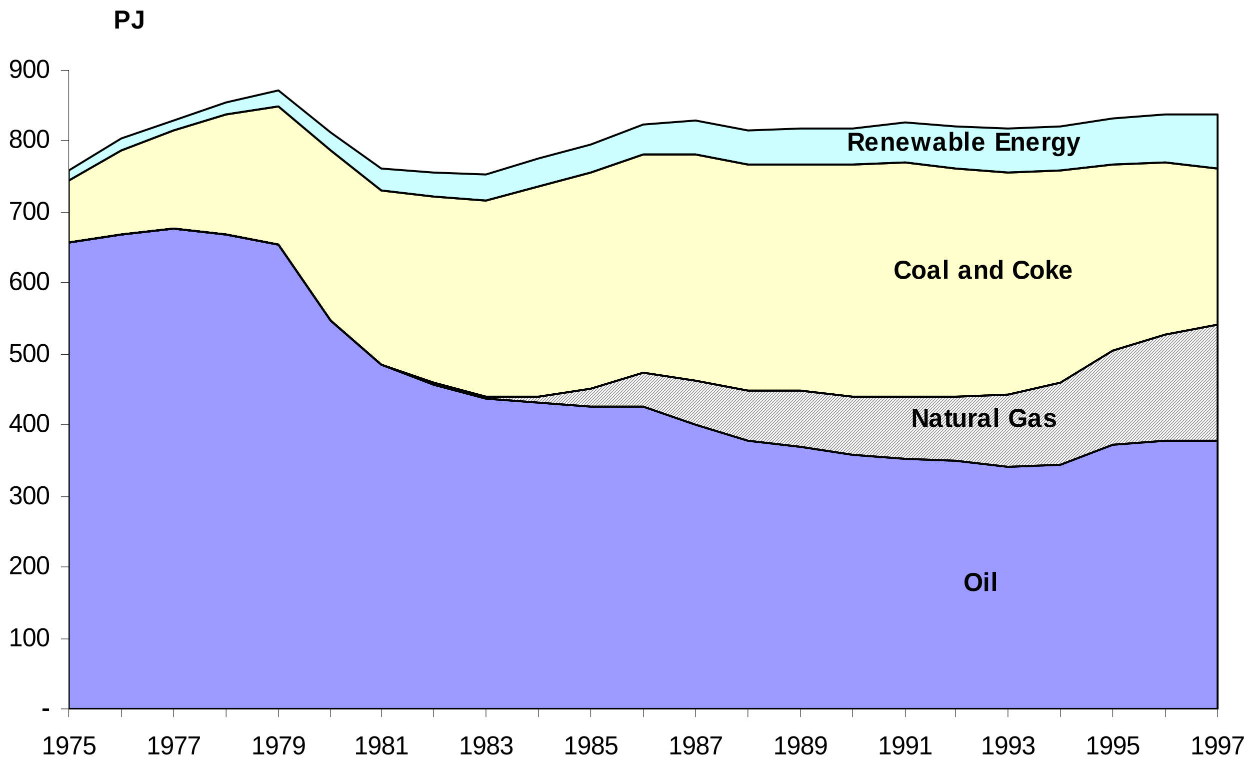

Figure 1 Primary energy consumption in Denmark 1975-1997 (adjusted for climate changes and net electricity exports)

Source: Danish Energy Agency

The gradual increase in renewable energy is another publicly planned change that has effects not only on the composition of primary energy, but also on the level of primary energy demand. The introduction of renewable energy takes place in the production of electricity and heat, and increases the average energy conversion efficiency. This will contribute to a reduction in the total primary energy demand.

There is a difference in the development of energy as an input factor of production and of energy directly consumed by households. Figure 2 shows the two patterns.

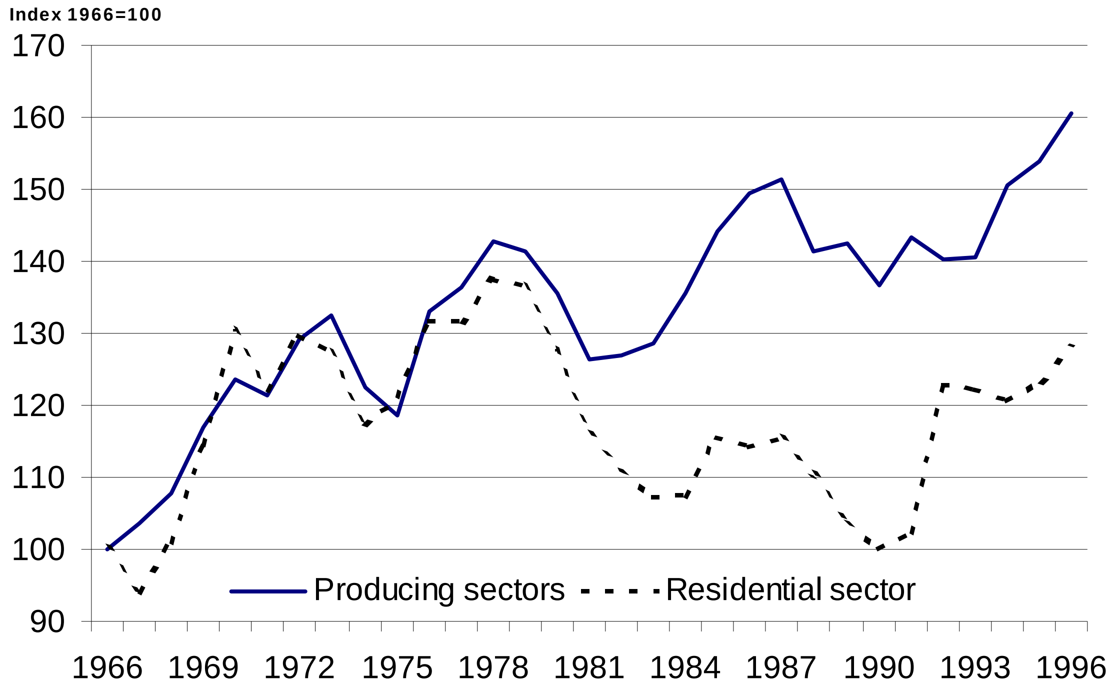

Figure 2 Primary energy consumption 1966-1996 (not adjusted for climate)

Primary energy consumption has been increased in the producing sectors, where consumption in the residential sector has been considerably reduced since 1978. This reduction is a result of a number of factors of which the very detailed regulation and taxing of residential energy use is important in combination with the use of subsidies and the large public investment in natural gas and district heating networks.

There are considerable structural changes in the energy demand in both the residential and producing sectors during the period 1966 to 1992. This is reflected in the tables below covering energy demand and composition on types of energy for both sectors.

	electricity			other fuels			transport		
	1966	1992	Change	1966	1992	Change	1966	1992	Change
Primary[2] energy (TJ)	35927	86874	142%	185661	114212	-38%	30954	63615	106%
Energy costs[3] (mill. DKK)	518	8624		1325	13276		1068	7856	
Energy cost share[4]	1.13%	1.93%	71%	2.88%	2.97%	3%	2.32%	1.76%	-24%

Table 1 Growth of residential energy demand 1966-1992

[2] Electricity is represented by the primary fuels used for the production of electricity

[3] Current prices

[4] Current energy costs divided by total private consumption in current prices.

Different parts of residential energy demand are driven by different activity parameters such as housing area, number of cars or the stock of electric appliances. Residential demand for heating in Denmark has grown slowly as measured in primary energy terms. The demand for electricity has increased very much and transport energy demand has also been rising fast. Transport energy demand has grown faster due to a continued increase in the stock of vehicles, and is seen as one of the main future contributors to increased energy demand. Contrary to this, the demand for other fuels, which together with a small fraction of electricity constitutes heating fuels demand, has decreased by more than one-third. The very intensive energy planning and regulation in the area of residential heating have decreased primary energy consumption. Some of the decrease is caused by the increasing share of district heating, which in the energy matrices used here is produced with very high conversion efficiency[5].

Contrary to the decrease in demand for other fuels, the cost of these fuels has been rising considerably, thereby causing a small increase in the cost share of these fuels The cost of other fuels also constitutes the largest fraction of residential costs for energy. For transport fuel demand, the cost share has been decreased despite the large increase in demand. This supports the widespread opinion that private transport energy use has been partly exempted from the heavy taxation that electricity and fuels for heating have been experiencing.

	electricity			other fuels			transport		
	1966	1992	Change	1966	1992	Change	1966	1992	Change
Service sector	3784	22301	489%	42782	24450	-43%	46847	88973	90%
Manufacturing	9788	30682	213%	109483	80351	-27%	4106	6406	56%
Agriculture	3172	5760	82%	17972	10026	-44%	14918	16426	10%
Construction	1080	1195	11%	3484	3128	-10%	6219	10985	77%
Total	19703	73637	274%	190501	140094	-26%	84138	138892	65%

Table 2 Growth of different parts of energy demand 1966-1992

Some long-term trends can be identified. Electricity has increased its importance as the main energy input for production. This is seen for almost every subsector in both service and manufacturing. For manufacturing, electricity has increased very much in importance for the main part of manufacturing industries. For the few very energy-intensive manufacturing industries, the share of electricity is lower but the share has increased very much from 1966-1992 (see Table 2. in the first paper on energy and trade). While manufacturing industry has reduced the energy intensity, the service sectors show, in contrast to this, a more stable energy intensity.

For the producing sectors, electricity consumption has also been the fastest growing segment of energy demand. Large differences are seen between the sectors, which to some extent is a result of different production developments. Figures like the ones above should always be compared to energy intensities, as is done in the last paper on trade patterns. Electricity use has increased while the use of other fuels have decreased in all sectors. There is a large decrease in the use of other fuels in the service sector. This is a result of substitution in favour of electricity for some part and a general decrease in

[5] Data for primary use of waste, straw etc. is not included and the large Combined Heat and Power producers attributes only a very small share of fuel to their production of heat.

demand for another part, where more efficient room heating in service is especially a main issue[6].

Structural change in energy demand has been of a considerable size in the period 1966-92 and is a very important issue for any attempt to project energy demand, or design a policy to achieve, for example, emission reductions. The issue of structural change is discussed in some of the following sections of this introduction and is also the topic for the paper about structural change in the energy supply sector and one about the structural change of Danish trade patterns.

3. Projection of long-term energy demand in Denmark

In Denmark there has been considerable focus on all areas of energy production and consumption. The authorities have planned the energy sector, and for more than 25 years policies have been directed at reducing the growth of energy demand. Raising prices by taxing energy use, especially for residential use, in combination with a number of subsidies to improve energy efficiency, and research have contributed to the low per capita energy consumption in Denmark relative to other industrialised countries. Direct regulation and control have played a major role in energy planning, and the projection of demand has been strongly influenced by the important parameters under public control via the detailed long-term planning. The detailed planning of heat and power supplies as well as the public networks of district heating and gas supply have been central inputs to all aggregate energy demand projections. The same has been the case of the regulated pricing of electricity and natural gas. Because of the highly regulated environment, the type of model that has been used to project demand has been very detailed. Models based on physical restrictions and planning parameters have been used along with optimisation models.

To facilitate this public planning and examine possible policies, a number of models were developed. The objectives, methods and theoretical background vary quite a bit among the models. The macroeconomic models played only a minor role in designing energy policy. Their most important contribution was to address the consequences of high oil prices and emphasise the sensitivity of the Danish economy, especially the current account, to the international oil price rises around 1980. A number of optimisation models for the energy system were developed, however most of them lacked any connection or linkages to the rest of the economy. Detailed power and heat planning as well as models dealing with residential energy use played a major role.

The making of demand projections with these models is an integral part of energy planning, and is also an analytical tool for the utilities of today. Within the administration it is not only the Ministry of Energy and Environment but also the Ministry of Finance, Ministry of Economic Affairs and Ministry of Business and Industry that carry out forecasts of energy demand for their interior use.

With the different models, but just as often with the same models, the projections vary a lot. Until now what has been exceptional is the long-term projection. Not many policy makers or managers of utilities are concerned about energy demand 30 years from now. The technical models with projections of 30 years horizon have been heavily criticised for the uncertainty about demand. Uncertainty about growth prospects, technical progress and even demography are dominant with respect to such a time horizon.

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[6] The same comment as for residential heating applies to district heating used in producing sectors.

4. What is the overall opinion on the development of long-term energy demand in Denmark?

It is widely expected that energy intensity will continue to decline as the composition of final demand moves in the direction of more service and less processed products. It is also commonly accepted that technological progress will continue to reduce the energy needed for production processes and household service levels. But it is not broadly clarified whether these energy demand-reducing effects can outweigh the effect of increased private consumption and the production required to satisfy it.

The Danish energy plans[7] expect a decrease of 17% of primary energy consumption from 1994 to 2030. This ambitious target is expected to be realised by continuing and extending the efforts of the earlier energy plans. Without the additional measures included in the latest plan the primary energy consumption would be expected to increase by a modest 10% in the same period. This figure does not seem out of line with the development observed for the last 25 years, as discussed above. A remark to raise here is the possibility that the structural change that has occurred in the last 25 years and a possible structural change of the economy to appear in the future can have important implications for the long-term energy demand projection for Denmark.

The importance of structural change in the energy supply sector has been emphasised by the earlier energy plans that have contributed considerably to the changes occurring in the sector. New structural changes with respect to changes in both organisation and the competitive environment for the energy supply industries have also received much attention in Denmark recently, even though this issue has had limited impact on the actual projection.

Other structural changes have received less attention: (1) the composition of private consumption on different categories of goods, (2) the effect of a transition to production where the cost share of energy input is very small in all sectors, apart from a couple of exemptions, and finally (3) the change in the structure of foreign trade.

With respect to structural change of trade, it is expected that a continued process of globalisation will tend to reduce the demand for energy as an input in production for countries such as Denmark. The papers about trade patterns and long-term energy demand are intended to investigate this hypothesis in greater detail.

In any event, the papers in this collection are intended to analyse in detail some of the structural change issues, but they cannot resolve the controversy among energy planners and modellers over the strength of the flattening of future energy demand in Denmark.

5. Economic growth and energy demand: Is energy a prerequisite for growth?

Energy is an input in the production process, but is it also a necessary input for all production activities? Certainly some energy input is needed for the working of the aggregated production economy, but it is possible that a significantly increased production can occur without the need for more energy. The endogenous growth with environmental resources literature considers the possibilities of having permanent growth without exhausting the non-renewable resources. This seems possible under some restrictions for the technological progress created by private decisions. This literature assumes that the renewable resource is an elementary input, but the efficiency of energy can be improved with R&D creating new and more efficient varieties of

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[7] Energi 21: The Danish Government's Action Plan (April 1996).

capital. Other views of possible growth without the additional input of energy is, for example, reflected in the discussion of influencing consumer preferences towards the picture of a "green consumer" as discussed in a following section.

In the Danish case, the energy intensity of the economy is very low compared to international standards. In production the energy intensity is especially low, and it is in theory possible that a small country like Denmark could expand its production considerably by only a very modest increase in energy demand. This could be achieved if all the energy-consuming parts of the production process were carried out abroad or energy-intense intermediate products, such as aluminium, were all imported. But this is only long-term energy demand in Denmark and does not address the global issue of conditions necessary to achieve economic growth without a corresponding growth in primary energy requirements. Issues related to trade and energy demand are covered in the last two papers.

A production elasticity of unity is the most common assumption used in macroeconomic modelling of the relation between production and the input demand for energy. What is meant with energy input in this context? Most likely it is the services of energy input that is considered to be the relevant input. That means the production factor energy is to be considered in effective units and is not to be construed as the primary energy, which is embodied in the input.

Production elasticities have in some formulations been less than unity, which has been justified by including in this term the technological progress or structural change taking place within the entity being examined.

A possible de-coupling of GDP and energy demand has been discussed a great deal. The hypothesis that these two can be decoupled is very unclear, as it seems to assume that GDP is the only factor driving demand. Is it a permanent de-coupling? In other words, will energy demand not grow with the economy when all other factors, such as energy prices, tax structure and relative input prices are constant?

6. The income elasticity of energy demand

The income elasticity of energy is an important issue for long-term energy demand. The basic question here is whether or not energy consumption will increase at the same rate as national income. The income elasticity question can be divided into two separate categories, based on the distinction between energy used directly by households as an energy service and energy used as an input for production. The consumption pattern for an individual cannot be expected to be as stable as production functions, which is the reason that unitary income elasticity is less frequently imposed for estimations of residential energy demand than for production use.

For the direct use of energy in households, some basic characteristics are important.

How should energy be characterised?

- Is it a homogeneous good?
- Is it a luxury?
- Is it a basic need?

Energy for residential use is certainly not a homogenous good, with large substitutability between the types of energy. For example, electricity, at least until now, has not been a substitute for transport fuels as private transport cannot be substituted for by use of electric appliances as consumption goods.

The luxury characterisation of energy is very relative depending on both the economic and geographical contexts. In a high-income country, electricity can to a large extent be considered a basic need to run all the appliances found in every household, such as a refrigerator and television. In a rural low-income society, on the other hand, electricity will be a luxury item affordable by only the few. Although transport fuels are considered to be a necessity in some rural areas, they are a luxury in cities of the same high-income country. The reason for this is simply that alternative transport options are available in cities and daily transport needs are of a limited size. The income elasticity of electricity might be lower than for gasoline, but it still depends on many other factors as well. For ordinary citizens the income elasticity of gasoline might be high, whereas for households in rural areas the gasoline demand is initiated by a basic need for transport in situations where there are no alternatives.

The income elasticity can be examined and estimated from an aggregate view of a country as, for example, Denmark in the study by Bentzen (1993b). This can be done also by considering the large fraction of total energy demand that is directly consumed by the households consisting of fuels for transport, heating and electricity for electric appliances.

In an econometric study of long-term energy demand for seven major OECD countries 1960-1990, Jones (1994) found that a unitary income elasticity could not be rejected, regardless of whether or not a time trend for technology were included.

Bentzen (1993b) examines Danish energy demand for the period from 1900-1991 using co-integration techniques. He finds only weak evidence for a long-term relationship between energy demand, income and energy prices. However, the income elasticity in different specifications and for different subperiods remains close to unity.

Bentzen examines aggregate Danish data, where the production elasticities in the macroeconometric model ADAM[8] are for all of the 19 sectors. In ADAM, production elasticities are tied to unity in the long run. This is a natural choice if a trend is included in the estimation and the intention is that the trend should capture a possible long-term trend in efficiency. The same applies to the INDUS model[9].

If the production elasticity is tied to unity the trend will if interpreted as efficiency be too optimistic if there should be other explanations for the reduced energy content. This could be, for example, a shift in the composition of the outputs within the sector. Therefore, the trend must always be interpreted cautiously as incorporating a range of different elements.

7. Fuel prices and long-term energy demand

This is probably the issue in relation to energy demand that has been given the most attention from economists. From an economic perspective this is the obvious target for a policy to reduce the growth in energy demand. A large number of studies have estimated price elasticities for all different aggregates of final energy demand, fuels or energy services. Their results have been mixed with respect to the size of elasticities, but in general elasticities are not too high, and in most cases considerably less elastic than -1.

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[8] ADAM: Annual Danish Aggregated Model, Danmarks Statistik (1996).

[9] INDUS 3: A model of energy demand in primary producing sectors: Model documentation and estimation results. Draft version, February 1999.

For Denmark fuel prices have varied a great deal during this century. Data for real energy prices for consumers in the Bentzen (1993b) study shows large variations, but the most interesting observation is the relatively low prices today compared to the average of the century. Bentzen finds very low price elasticity for Denmark on data covering the period 1900-1991. The elasticity is found to be –0.13 for the whole period if data for primary energy consumption are examined and –0.21 for the period 1930-1991. If data for net energy consumption 1930-1991 are used instead, the price elasticity is –0.27. In the case where net energy is used, the composition effect (e.g. a trend towards electricity) can generate problems for an estimation as in Bentzen where no trend is included.

ADAM has long-term price elasticities ranging between -0.1 and -0.35 for manufacturing industries with an average of -0.25. ADAM estimates are based on 1948-1990 data and conducted for 14 industries. The 1998 INDUS model is based on 1966-1992 data for another classification of industries and with separate estimates for electricity, transport and other energy demand for 26 industries. Here the long-term elasticities range from –0.17 in fabricated metal products to –0.85 in paper and pulp for electricity, and from –0.10 in transport equipment to –0.34 in cement production for other fuels. The INDUS model is more disaggregated than ADAM and this seem to result in both more variation in elasticity estimates and more elastic estimates for price elasticities, on average.

One important difference between the specification used by Bentzen and the other studies is the inclusion of a trend to take account of unexplained elements of the series, caused for example by improved energy efficiency, structural change of the sector or a change in the product mix. Another difference is that Bentzen examines energy input both in production and private use.

One explanation for the lack of interest in energy prices can be the very small cost share for energy in production costs in Danish industries, on average. Energy generally accounts for only around 2% of production costs. Another explanation can be that the rise of oil prices caused a development of energy technology that diffuses through the capital stock only slowly and gradually and as a consequence "gets caught" by the trend term in the estimations.

The relative low estimates of price elasticity have implications for policy analyses of tax proposals and cost estimates of certain targets for energy or emissions reductions. The low price elasticities also affect the long-term forecast properties of the model. The forecast will depend to a large extent on the exogenous predictions of trend parameters. In this way the long-term energy demand forecasts will be increasingly dependent on any forecast and explanation of **efficiency developments**, which has been chosen as the topic for the first two papers in this collection.

The policy consequences of using only price-related instruments in model analyses have been found to be considerable with respect to losses in welfare, GDP or consumption unless double dividends from different kinds of revenue recycling principles are taken into account. The costs of these tax policies have increased the interest for other possible policies that might reduce energy demand. Policies have been considered to promote the utilisation of the best available technologies and increase innovation rates for more energy-efficient production equipment. Some attempts to include these two technology questions in energy-economy modelling and describe policy options for influencing these issues are covered by the two papers on technology following this general introduction.

Fuel prices and technological progress are related by the obvious fact that energy prices affect both the choice between capital equipment with different energy efficiencies, as well as the effort put into improving energy efficiency and developing more energy-efficient equipment. This relationship will in many cases of modelling be included in the long-term price elasticity and probably will also be the main explanation for the difference between short- and long-term price elasticities.

The Danish policy to reduce energy consumption and its environmental impact has been based partly on imposing high taxes on energy use. This has been the case for the residential sector, which compared with other countries has paid very high energy prices. Production sectors have in contrast been charged only very modest taxes, based on concerns for international competitiveness.

8. Economic modelling of long-term energy demand in Denmark

Economic modelling of energy follows economic theory in the way that energy is an input to production processes or a service consumed by individuals. Like any commodity, the relative price of energy is an important determinant for its demand. Substitution possibilities among energy and other input factors are the reason that changes in the relative price of energy give rise to changes in demand. The existence of substitution options in all different specific instances of energy use have been debated and questioned. There is no doubt that energy, in some instances, substitute other production inputs and in other cases are complementary to them. Much of the modelling effort has been based on the assumption of energy being a substitute for labour, and labour and energy being complementary. If there are long-term trends in the capital/output ratio this complementarity has important long-term implications for energy demand. Energy intensity will thus be increased along with the increase in capital intensity.

The issues of technological progress and diffusion of technologies have barely been addressed by the models. To a large extent this is based on the difficulties of empirically estimating any plausible explanations for developments in energy efficiency. Also economic theory has not been too successful in setting up a convincing explanation of technological progress.

In Denmark, economic modelling of energy issues has received more attention in recent years in the light of the public focus on the economic costs of the ambitious national target of reducing CO_2 emissions by 20% in 2005 compared with 1988 levels.

In recent years a number of CGE models of the Danish economy have been developed including a description of energy issues, which in most cases have been initiated for environmental reasons. The GESMEC model (Frandsen et. al, 1994 and 1996) and the ELEPHANT model, both developed in The Economic Council, are examples of an economy-oriented CGE model and an energy system-oriented CGE model, respectively. The MOBIDK model developed by a team in The Ministry of Business and Industry (Harrison et. al., 1997) is an example of a disaggregated CGE core model. It has been applied in a number of energy-related analyses with specially designed extensions of the core model[10].

[10] Jensen (1998) and Jensen and Rasmussen (1998) are examples of applications.

The ADAM model, already with a long tradition for including energy and energy sectors in the model, improved the energy input relations. In the ADAM 1995 version (Danmarks Statistik, 1996) energy demand relations were included.

The ADAM energy and emission submodules, called EMMA (Møller Andersen et. al. 1997 and 1998), is another example of how the capabilities of a macroeconomic model to analyse energy policies is improved.

The third paper is an example of a combination of two different approaches to modelling energy-economy relationships: These are the top-down macroeconomic model approach as reflected in the above-mentioned models and bottom-up energy modules for energy supply and residential energy demand. It is shown that it is possible to integrate the two approaches in the case of specific Danish models. The paper shows important implications for long-term energy policy design. Typical top-down policy variables, such as a CO_2 tax, interact with bottom-up policy instruments in the form of direct planning of the energy supply sector and standards for electric appliances used by the households. The combined effect of the policy instruments to reduce CO_2 emission in the long run is considerably reduced compared with adding the reductions achieved when the instruments are analysed in separate models. A parallel can be drawn to the analytical results referred to in the first paper. The combination of "negative" externalities connected to energy input in production, "positive externalities" in the R&D sector and imperfect competition in, e.g. the capital good producing sector can make a combined policy package to reduce energy-related pollution a better policy than the traditionally suggested one-sided economic policy of a tax or a tradable permit system[11]. The parallel conclusion is that a policy, which consists of both market-oriented elements as a CO_2 tax and direct regulation should be considered and analysed in an integrated model. The prevailing energy policy in Denmark with its combination of different instruments might thus not be so bad a situation even from an economic point of view.

9. Technological progress

The issue of the speed and direction of technological progress is among the most important determinants for both the level and the composition of long-term energy demand. Uncertainty is inevitably tied to future technological progress and has been a major consideration in the discussions about the possibilities of reducing the growth of energy demand and emissions related to this growth.

The main question to consider is whether technological progress can be influenced by any public policy and whether the links between policy variables, the overall economy and technological progress can be adequately described in energy-economy models.

Two papers directly address the issue of technological progress. The first paper, following this general introduction, surveys different approaches to modelling technological progress that directly or indirectly influence energy demand. It also compares two Danish models with respect to their energy demand projections and the dependence on the various descriptions and assumptions made about future technological progress. It is found that the distinction between technological innovation and diffusion is important for identifying the policy options that can be used to accelerate these two elements of technological progress. Another result is that in the two

[11] Schneider and Goulder (1997), Carraro and Galeotti (1997, 1998)

Danish models it is not the assumptions made about the rate of technological progress that is the main reason for the very different energy demand projections produced by the two applied models.

The second paper deals with the issue of technology diffusion. The diffusion of technology is important when discussing options for increasing the rate of implementation of new energy technologies. Diffusion depends on economic and physical factors. For capital equipment with long physical lifetimes, vintage models with details on energy efficiency for the different vintages can yield important information. Vintage models are found to describe technology diffusion, and the analysis of Danish vintage models shows that diffusion can have a relatively long-term impact on the average efficiency, especially in the heat and power sector.

10. Structural change of the economy

Under this heading a number of different issues can be addressed. Structural change for a single sector that accounts for a large fraction of national energy consumption, can be addressed, as in the paper on the energy supply sector included here. Large shifts in the composition of final demand is another structural issue, as is the question of structural changes in trade patterns.

Most often the meaning of structural change is related to the composition of the domestic production. This has been the target for many decomposition studies that have tried to quantify the impact of change in the input-output structure on energy demand, energy intensity or emissions.

Many CGE models have been constructed to analyse energy issues or the more specific question of coping with the costs of emission mitigation. One of the advantages of those models is the explicit description of the structural adjustment of the economy and as well the energy demand consequences of structural changes. The most energy-relevant weakness is the lack of a description for technological progress. Also these models in many cases have a standardised technology for all industries, where energy is treated as an aggregate with the same substitution against labour and capital even though there are substitution options among different energy types in the aggregate.

11. Trade patterns are important structural parameters for energy demand in a small open economy

Trade and environment have received considerable attention in both applied studies and theoretical work.[12] Two recent special issues of environmental journals[13] and books by, for example, Carraro (1994) and Rauscher (1997) have been devoted to these subjects. Much of the applied literature deals with the pollution heaven hypothesis, namely, that polluting industries will relocate to areas of the world where environmental regulation and standards are being dumped. Johnstone (1995) is also concerned with this issue and presents a number of arguments related to trade liberalisation and its environmental implications. He argues that there are many reasons that trade liberalisation could have environmental implications. However, he finds that one aspect has been neglected, and that is the impact of specialisation and homogenisation on ecosystems. A number of

[12] For a recent overview of methodologies see van Beers and van den Bergh (1996)

[13] Resource and Energy Economics19 (4), 1997 and Ecological Economics 9 (1), 1994

studies have been looking at the NAFTA complex both before the implementation of the agreement and afterwards.[14]

Even though much of the literature is concerned with trade and environment in general, a large part is examining also energy-related polluting activities. Therefore, an analysis of Danish trade patterns and energy demand is related to this broad trade and environment theme.

Energy consumption taking place in Denmark can be influenced to a large extent by the patterns of foreign trade. The integration with world markets has been steadily increasing and as a consequence, a large share of the energy consumption taking place in Denmark is a direct result of the demand for exports. Corresponding to this, a large part of the Danish intermediate inputs and final demand are produced abroad, where energy is consumed outside of Denmark.

The energy content of imports cannot be identified, because too many countries and goods are involved. The usual way of addressing this problem is by examining the global energy content of imports as having the same energy content as locally produced goods of the same category. There are two major problems with this approach. First the technology is certainly different especially with regard to the primary fuels used domestically and globally, and secondly the products produced domestically will in many cases differ from those imported. Studies that use estimates of energy content of imported goods from different regions are available (Wyckoff and Roop, 1994), (Battjes et. al., 1997).

Figure 3 shows the energy intensity of exports and imports calculated as global energy content. All the series in this graph follow similar trends, with imports being slightly more energy intensive than exports. It is surprising that manufactured imports have experienced a larger reduction in energy intensity than total imports and especially manufactured *exports*. There is no indication here that the composition of goods produced in the manufacturing sector has shifted towards less energy-intensive production relative to the composition of manufacturing imports. It must be noted that the energy intensity series are a result of a combination of Danish production structural change and a composition effect in exports and imports.

[14] Grossman and Krueger (1991), Gale (1995)

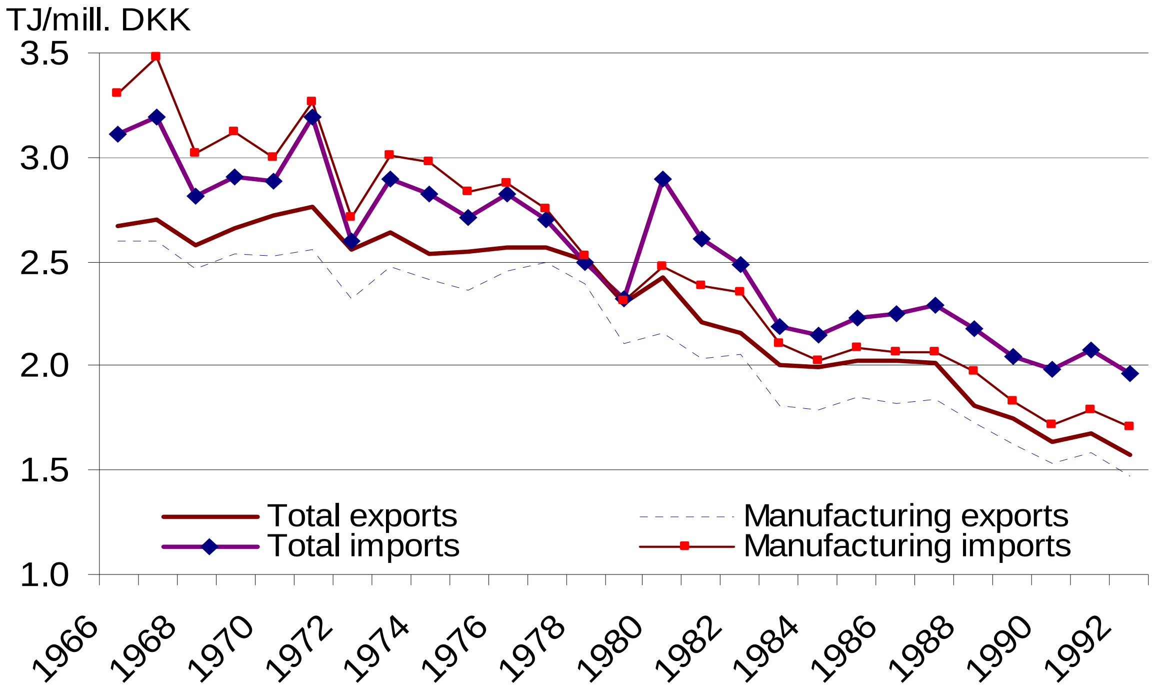

Figure 3 Energy intensity in Danish exports and imports

The intensity data in the figure describe trends in global energy content of Danish exports and imports and not the actual energy consumption in Denmark. Despite the large reduction of energy intensity in manufacturing imports the Danish energy consumption created by exports might have been reduced more than the global energy content if imports of intermediate inputs on average were to have become relatively more energy intensive. The aggregate data presented in the figure is also based on the relatively low energy intensity of Danish production, which implies that the aggregate figures are dominated by the main group of Danish industries with low and very similar energy intensities.

To analyse the more disaggregated effects of trade changes and the impact on Danish energy consumption, information on different elements influencing energy demand in Danish production must be included in the analysis. For example, it is obvious that most of the decline in energy intensity seen in Figure 3 is a result of a general improvement in energy efficiency, to some extent caused by more electricity input in the economy and more efficient electricity production.

The issue of trade and energy is addressed in two of the papers included in here. The first paper is an introduction to the export consequences of changing energy technologies and to the export effect of a policy to promote renewable energy technologies. The most energy-intensive industries in Denmark could be supposed to have performed relatively poorer with respect to production and export than the average industry due to the strict regulation and lack of energy price discounts in Denmark for those industries. Data for the period 1966-1992 give only weak support to this hypothesis. Production has been poorer than average, but the export performance compares well with the average manufacturing industry. Another issue is the very large contribution to exports found for exports of only two items with environmentally friendly energy characteristics, namely, wind turbines and district heating pipelines, which constitute more than 2% of the total Danish manufacturing export. Thus in this case, the Danish policy of supporting the development of these new technologies together with the domestic market backup have given rise to considerable export potentials.

The second paper is an input-output decomposition analysis of the importance of changes in trade patterns for energy demand. The effect of trade changes for a small open economy, Denmark, is examined with respect to the contribution of trade to the change in energy consumption in 117 Danish industries over the period 1966-1992. It could be expected that Denmark as an advanced industrialised country with an increasing input of both human capital and R&D would have reduced its share of production in heavy industry. The energy consumption in Denmark is assumed reduced by increasing imports of goods produced in the energy-intensive sectors as well as by increasing exports of those goods and services that have been produced with a large content of skilled and academic manpower and only little energy. This is not reflected in the study reported in the last paper. Instead, the change in the economy from experiencing a considerable trade deficit to a remarkable trade surplus has increased energy consumption in Danish manufacturing by more than 10%. The issue of trade is thus an important one for all considerations relevant for Denmark when entering into international agreements on CO_2 emissions. For a small country as Denmark the difference between developments in the energy that is used directly within Denmark and the development in energy content in final consumption can be quite large.

A technical conclusion that is reached from the decomposition analysis is that aggregation certainly matters. The very large differences in the energy intensity within an aggregate sector in combination with large differences in the influence of trade developments on the same sectors can produce totally different results for decomposition analyses performed on different levels of aggregation. Analyses of this kind should be performed on the most disaggregated data. Many of the decomposition studies, which compare results for a number of countries, are performed at a rather aggregated level and their results should be interpreted cautiously.

12. Physical infrastructure etc.

The infrastructure of a given society is relatively long lived. In the long run the energy demand will depend on how the infrastructure develops. The most obvious case, which comes to mind, is the development of transport demand, both passenger and freight. Bridges, for example, create travel opportunities for individuals. When first build no one would expect any restrictions of use based on a purpose of limiting the growth in energy use.

As infrastructure is a very publicly planned issue, developing it is also a policy instrument to be considered. In many cases, the focus of infrastructure has been on infrastructure for the supply of energy goods and services. Increasing the efficiency of energy supply has been highlighted as one way to reduce energy demand growth.

In Denmark, these energy supply options have been exploited in a very successful way, as efficiency in the use of energy has been given a much higher priority than economic efficiency. The infrastructure for networks of district heating and natural gas has been supported and to a high degree also financed through public funding. This long tradition in Denmark has had a substantial impact on both the level and composition of energy consumption in the residential sector. In this sector very large improvements in energy efficiency have been achieved, especially through the widespread supply of district heating based on combined heat and power. Fewer infrastructure projects of this kind are planned for the future, as both natural gas and district heating coverage are close to their limits. But the existing networks can be very useful if they can be used successfully for distributing potential new sources of energy, as for example hydrogen.

An important part of a country's infrastructure is the housing sector of the population. This has very long-term implications for energy demand through the need for heating and cooling as well as for lighting. At the same time, the settlement pattern gives rise to a demand for transport facilities, roads, public transport, the extension of energy networks etc.

Infrastructure of a different kind can become a critical parameter for transport energy demand. The Internet and displacement of the worker from the conventional work place could change the transport needs of modern society. Transport needs could be considerable reduced by a more widespread use of working home. But the effect on transport might be minimal if people locate their families more remote and thereby keeps weekly transport needs unchanged even though they go to work less frequently.

Physical infrastructure in general is not covered in this thesis, but it is one of the issues in the fifth paper dealing with the structural change of the energy sector. The very long-term public planning of district heating networks as well as the distribution networks for natural gas is one of the public decisions about infrastructure that have had the largest impact on combined heat and power efficiency and the composition of primary energy demand.

13. Demography

When the horizon extends more than 10 years, the change in population is an important factor in describing energy demand. This factor is easily underestimated in importance because it is always included in both the economic models and technical bottom-up models. However, it is always an exogenous representation of the development in the number of households, people per household etc.

The uncertainty about demographic developments is greater than is often recognised, judged from the comparison between population data in the more recent population projections from Statistics Denmark. The change in fertility and immigration patterns has been quite large, and the population projection in the long-term has been increased significantly.

Demographic patterns can have long-term effects also through the composition of the population on different age groups. Consumption patterns and the economical focus is different for young families and the elderly. Transport will be influenced by the increase in the very old population, as hardly anyone beyond 80 years is an active driver. At the same time, old people live in smaller flats and do not utilise/heat all the rooms in their dwellings. Thus, demographic patterns must be included as one of the structural parameters influencing long-term energy demand.

The last 20 years has resulted in an increased percentage and number of people living alone, and the average size of a Danish household has subsequently declined. This shift has certainly also led to an increase in residential energy consumption, and the projection for this change in average household size is important for predicting future energy demand.

The importance of demographic developments and the uncertainty connected to them has been emphasised here, but this topic will not be covered any further in the rest of this thesis as the topic is considered to be only loosely connected to the main topic of structural change of the economy.

14. Lifestyle issues and green consumers

The issue of lifestyle has received some attention both in ecological economics and in sociological studies of consumer behaviour.

This issue goes beyond economics in that it basically assumes some possibility of influencing the preferences of consumers. On the other hand, many empirical studies examine the differences among consumer groups. Is there a difference between ordinary consumers and green consumers in a society? Is this possible difference caused by variations in wealth or is it totally independent of economic factors?

The lifestyle issue has also focused on people belonging to different socio-economic groups in society or the rural versus city dweller.

For long-term energy demand, the question of a possible change in lifestyle or a shift of preferences has important implications. Not only is the consumer preference for a green variety of a specific product important, but to an even larger extent a basic shift towards much more polluting leisure-time activities, as e.g. excessive travelling and search for adventures.

Some economists would argue that lifestyle changes in the direction of green consumers represent more of an attitude, but when it comes to choosing between similar products with different green characteristics, the green consumers can hardly be distinguished from the non-green consumers.

One area where lifestyle matters is housing. Will everybody prefer apartment dwelling or houses with large gardens? Do we take showers every day or only twice a week? Do we expect personal habits like this to change?

Other examples are found in the way that we spend our spare time. Do we sit in front of the TV or do we go on a charter holiday? Walk in the forest or try out the new go-cart-lane.

The issue of lifestyle will not be gone into beyond merely mentioning it here because of the problems noted above of distinguishing between the behaviour of the different lifestyle groups in aggregate data and also because this has been the focus of a number of Danish studies conducted recently. The main focus has been on macroeconomic structural change, and indirectly changes in lifestyle will be partly reflected in the composition of private consumption and production.

Technological progress and long-term energy demand. A survey of recent approaches and analysis of a Danish case[1]

Henrik Klinge Jacobsen*

Working Paper, February 1999

Abstract

This paper discusses different approaches to incorporating technological progress in energy-economy models and the effect on long-term energy demand projections. Approaches to modelling based on an exogenous annual change of energy efficiency to an endogenous explanation of innovation for energy technologies are covered.

Technological progress is an important issue for modelling long-term energy demand and is often characterised as the main contributor to the different energy demand forecasts from different models. New economic theoretical developments in the fields of endogenous growth and industrial organisation have important implications for the attempts to endogenise technological innovation and diffusion of new energy technologies. A range of analytical and empirical models with different description of technological progress is surveyed in the paper. The important difference between technological innovation and diffusion is emphasised especially with respect to the implications for energy- and environmental policy.

To analyse the importance of the technology description, two models of residential energy demand in Denmark are compared. A Danish macroeconometric model is compared to a technological vintage model that is covering electricity consumption for electric appliances and energy consumption for residential heating purposes. The energy demand projection of the two models diverges, but the assumptions of technological progress cannot be directly compared in order to demonstrate whether or not these assumptions are the reason. The efficiencies of the vintages for all the electric appliances have to be aggregated and weighed with the assumptions made regarding the efficiencies of residential heating technologies.

Assumptions about energy efficiency improvement in the vintage models are found to be important for the projection. The vintage modelling approach is found to be less important for long-term projections. Also one limitation of the vintage modelling approach applied in the long-term explains some of the difference in projections among the two types of models. The applied vintage model of electric appliances does not adequately describe the category of new energy-consuming appliances that are expected to become available in the long-term. If it is to be used for long-term projections this category must be more carefully modelled.

JEL classification: O30; Q40
Keywords: energy demand, technological progress, energy-economy modelling

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[1] A previous version of this paper appeared in the proceedings of 19. Annual North American conference, Albuquerque, (US), 18-21 October 1998. (United States Association for Energy Economics; International Association for Energy Economics, Cleveland, OH, 1998), p. 143-152.

* Risø National Laboratory, Systems Analysis Department, PO. Box 49, 4000 Roskilde, Denmark.
Email: henrik.jacobsen@risoe.dk

1. Introduction

Technological progress is an important issue when modelling long-term energy demand. It is often argued that the difference in the assumptions that are made about technological progress is one of the main causes for the very divergent results, which have been obtained using bottom-up and top-down models to analyse the costs of greenhouse gas mitigation[2]. One of the objectives of studies that compare model results has been to create comparable model assumptions regarding technological progress[3]. In recent years the issue of technological progress has been increasingly connected with the debate over the timing of CO_2 emission abatement measures and policies[4].

The modelling of technological progress with respect to energy technology includes different aspects of technological progress. The main distinction is between modelling innovation and modelling diffusion of existing technologies. In this context innovation is interpreted as including the invention and improvement of a technology until its first actual use, whereas diffusion describes the process whereby a marketable product or technology is diffused throughout the economy.

Recent advances in economics have important implications for the modelling of technological progress within the field of innovation and long-term energy demand[5]. Carraro (1998) describes two such new economic research areas: endogenous growth and industrial organisation, both of which have had important impacts on environmental economics and the issue of innovation. These new research areas are also important in explaining the innovation of new and more efficient energy technologies and their resulting impact on long-term energy demand. The ideas have been implemented both in empirical modelling and in policy analysis in which one searches for alternatives to the traditional economic policy instruments that are used to reduce the growth in energy consumption and emissions of greenhouse gases.

In top-down-based energy-economy modelling, the description of energy efficiency improvement varies with respect to the focus on explaining the progress. The representations range from exogenous and constant rates of efficiency improvement AEEI (Autonomous Energy Efficiency Improvement) to attempts to endogenise technological progress. A constant AEEI can easily be criticised. On the other hand, it has been very difficult to empirically verify any of the assumed but also plausible relationships creating the endogenous progress.

The short- or medium-term developments in energy efficiency will depend on a variety of factors such as capacity utilisation, vintage effects from new investments, public policy, specific innovation of new technologies and implementation of already

[2] Carraro and Galeotti (1997) refer to the general agreement among both bottom-up and top-down modellers that the difference in the descriptions of technological progress is the most important explanation for the inequality between the results obtained with the two different kinds of models. Hourcade and Robinson (1996) argues that it is not the different modelling approaches but the actual assumptions put into the models that is causing different results in the studies of greenhouse gas mitigation costs.

[3] See various studies from Energy Modelling Forum, EMF, for example, (EMF, 1993).

[4] Wigley et al (1996) argue for postponed action, whereas Schneider and Goulder (1997) state the case for the introduction of taxes, but not necessarily abatement now. Both groups of investigators rely heavily on arguments related to technical progress.

[5] Toman (1998, p. 10) finds that “it is widely agreed that technical innovation is the ultimate key to successful global measures to stabilise the concentration of GHGs in the atmosphere” and point to this as an area where further research is particularly warranted.

known technologies. In this horizon the diffusion of technologies is just as important as the innovation of new technologies.

Here the bottom-up and technically based models can have an advantage in projecting this part of technological progress. In the disaggregated case technological progress can be represented by a specific invention and innovation of some equipment or as the diffusion of a new model of a specific electric appliance. The detailed assumptions about the expected improvement in the efficiency of a specific piece of equipment or technology can be aggregated and the effect on energy demand compared to the effect of using an aggregate energy-economic description for the development of energy efficiency. This is what is done in the second part of this paper.

In the long run the usefulness of a detailed bottom-up modelling of technological diffusion will decline and the description of innovation will be the dominant factor in explaining efficiency developments. This is illustrated by the bottom-up vintage model in the second part of this paper. One weakness of the vintage model applied for making long-term analyses is especially emphasised. In the vintage model the efficiency of each appliance is well determined but the aggregate of residential electric appliances misses some factors of energy demand. The categories of electric appliances change in time as new electricity consuming appliances are added to the number of existing appliances.

Top-down models are more suited to analyses of long-term innovation as they include behavioural relations to a larger extent and include also a consistent framework for analysing accumulated developments in knowledge and technology spill-overs between different sectors. Until recently the practical implementation of innovation explanations have been very limited in the energy-economy models, but this field of modelling receives much attention at present.

The first part of this paper describes different approaches to incorporating technological change into energy-economy modelling. First, in section 2 an overview is given of different approaches to empirical modelling, and then in section 3 a more thorough investigation is made of the innovation issue, which is central to all long-term energy demand analyses. In the second part of the paper different approaches in two Danish models are compared to examine whether the description of technological progress is the reason for the large difference in energy demand projections from the two models.

2. From autonomous energy efficiency improvement to endogenous technological innovation

Energy-economy models have very differing descriptions of technological change. At the same time technological change is an important element for model properties and the long-term projection results that can be obtained by a model. Model descriptions range from autonomous energy efficiency improvement (AEEI) to endogenous technological innovation. This section gives an overview of the different approaches, whereas the next section reviews specific issues related to modelling innovation.

The different approaches to modelling energy technology progress are related to the different orientations of the model, that is whether an approach is related to neoclassical growth theory, endogenous growth theory, industrial organisation, innovation literature, macroeconometric vintage models or technological optimisation and simulation models. Growth theory is concerned with long-term issues and hereby with technological progress as an exogenously given driving factor for growth in the case of neoclassical growth theory and with explanations of the growth of technological progress in endogenous growth theory. Analogous to this, the energy-economy models based on growth models have representations of technological progress ranging from exogenous to endogenous.

Industrial organisation theory has provided insight into incentives to innovate and adopt technologies depending on different product market structures and properties of R&D activities. This has been the basis for models focusing on policy issues and for comparing R&D subsidies to environmental taxes or direct regulation. The literature of innovation has been involved in discussions of learning among other issues, and this has led to attempts to include learning curves in descriptions of specific energy technologies.

The macroeconometric vintage models have been extended to the energy field with capital vintages having different energy efficiencies or substitution properties between energy and labour. Optimisation models have focused more on specific energy technologies, both for energy supply and end-use categories. This large group of models primarily makes indirect technology progress assumptions, as the availability and cost profiles of different energy technologies are assumed to change in time, and the optimising choice of technologies determines the aggregate efficiency development.

The technical bottom-up models with a very detailed description of technological progress for a large number of specific technologies assume the individual technological progress together with a degree of penetration for existing technologies. This leads to a well-documented aggregate assumption of technological diffusion but includes no element of innovation.

Some of the different approaches toward implementation of technological progress in energy-economy modelling can be categorised by:

- AEEI - exogenous and constant energy efficiency improvement
- AEEI- distinguishing between price-induced and time-induced improvements
- Vintage models of capital with energy efficiencies related to vintage (general economy-wide representation)
- Optimising long-term technology among some aggregate technologies with varying efficiencies (energy supply sector)
- Endogenous rate of implementation of known, best available technologies
- Endogenous rate of innovation - R & D related

The autonomous energy efficiency improvement AEEI is an exogenous improvement in energy efficiency in many top-down models. When forecasting, the energy efficiency is projected to rise by an exogenous rate each year, which in different model studies ranges from an annual efficiency improvement of 0.5% to 1.5%. Apart from this exogenous component of energy demand, the prices of production factors capital, labour and energy shift the factor input composition. As a consequence, the energy intensity of production also changes. The AEEI is time dependent but instead of remaining constant the autonomous efficiency change could follow estimated non-linear time trends. Jones (1994) examines the question of incorporating a technological trend in econometric studies of aggregate energy demand. He argues that there are several technical problems connected to including technical progress and thus also for using these technology trends for forecasting with macroeconomic models. The main problem is the difficulty of distinguishing between technical progress and long-term price effects. Jones finds econometric evidence that technical progress growth lies at around 1.5% annually concurrent with plausible long-term price elasticities. The long run income effects are not found to be significant.

A possible extension of this approach is to link the efficiency improvement to energy prices, but it will be hard to establish empirically a distinction between price-induced shifts in factor inputs and price-induced improvements of efficiency. Jorgenson and Wilcoxen (1990) include technological progress by allowing input prices to interact with a time trend. But there is no explicit explanation for this relationship.

Links to macroeconomic traditions of neo-classical growth theory and discussions of embodied and unembodied technological change are obvious. Neoclassical growth theory takes technological progress as an exogenous explanation for long-term growth just as in the case of the exogenous AEEI in energy-economy modelling. The embodiment of technological progress in each year's capital vintage is similar to the assumption of exogeneity of technological progress except for time and the size of the capital vintage.

In this way a connection to the large group of vintage models is established. Vintage of two different kinds exists. Macroeconometric models or dynamic general equilibrium models can include capital vintages with putty-clay capital properties. A totally different type of vintage model is a technically based bottom-up model like the ones used in the second part of this paper.

Vintage effects through different energy efficiencies for different vintages of capital could be important for year to year changes in energy efficiency. Vintage models can describe the diffusion of new technologies or improved technologies. This kind of vintage model of capital has been applied to fields of energy relevance. Both technical vintage models of durable consumer goods (appliances) and vintage models of energy supply exist. More macroeconomically based model approaches of capital vintages for producing sectors in general and their energy efficiency have also been proposed.

In the OECD Green model (Burniaux et. al., 1992), the substitution between energy and labour is more feasible in the most recent vintages. In such a setting a policy that speeds up capital adjustment or replacement rates will increase technological progress in the sense that energy to a higher extent can be substituted by other inputs.

Vintage models of the bottom-up type will often be more sector specific and based on technical approaches to technology adoption and diffusion, e.g. evident in the models of Danish residential energy demand used in the second part of this paper. Epidemic diffusion models have been incorporated in vintage models of appliances in households. While technological development in energy use in economic modelling is often considered in terms of a constant rate of change in energy efficiency, the technical view would emphasise the specific technologies and expert views on future efficiency and diffusion. The technical view includes limits on the increase in energy efficiency. For existing technologies these limits seem plausible. In contrast the technological change from an economic view is an aggregate of changes in production technology for existing products and a change in the output mix with a stream of new products partly produced with existing and partly with new capital equipment. The top-down AEEI approach lacks any assumption of limits for energy efficiency or decreasing rates of energy efficiency improvement in time. Only when production of a single output or a very specialised sector is examined will production technologies be modelled in detail by top-down modellers, and thus the properties from technological models will arise.

An important property of vintage modelling is that the vintage specification alone still doesn't include or explain the issue of **innovation,** but is mainly a description of technology diffusion.

Another indirect treatment of technological progress is found in the many optimisation models developed for the energy sector. These models include a large number of energy technologies, in which the availability of the technologies in time is sometimes described. For example, energy-economy models, where the choice between specific energy technologies is optimised. The choice of technology depend on the total discounted profits and are based on rational expectations, which take into consideration exogenous assumptions regarding the availability of the specific technology in time. The resulting average energy efficiency is then endogenous in the way that changes in prices by environmental taxation have an impact on the optimal choice of the technology. Models of this kind are developed mainly for optimising energy supply systems. Clarke and Edmonds (1993), in a model of energy technology choices and product price formation, point to an aspect of new technologies that could be important for the diffusion of new technologies, especially in relation to optimisation models. The production cost for every technology is related not only to the cost characteristics of the technology itself, but also to other factors such as: geographical location (transport), skills of the local workforce etc. New and on average more costly production technologies will enter the market. But the impact of a new technology on output prices will not be to increase prices; this is because the new technology will be employed only in the instance where the production cost using the new technology in a specific context is below the market price. This observation might explain why some technologies that, based on average production cost seem non-competitive yet manage to capture market shares anyhow. It could be added that new technologies might include more uncertainty on costs than existing ones. The producer who successfully introduces a new technology will have an advantage relative to the competitors. Many optimisation models include a backstop technology, in most cases a technology for carbon-free electricity production, such as wind power[6]. This can be either an existing technology, which will become competitive at a very high fuel price or high carbon-tax, or a synthetic technology, which is assumed to be developed at high fuel prices. The second case implies an assumed relationship between fuel prices and innovation. At high prices or high carbon taxes an enormous amount of R&D can be afforded to develop this backstop technology.

Endogenising technology diffusion or implementation of best available technologies characterise the models, where the diffusion is described as dependent on a number of factors, for example, R&D, investment subsidies, fuel prices, market structure and with a specific modelling of firm behaviour. In a model for Austria, Glueck and Schleicher (1995) examine possible effects on technological progress of CO_2 reduction policies. This is an example of policies that can accelerate the diffusion of more energy-efficient technologies. But the study does not address the issue of technological progress in the form of the innovation and improvement of energy technologies. In the WARM model (Carraro and Galeotti, 1997) the diffusion of environmentally friendly technologies is also endogenised, and a policy instrument is introduced for subsidising the investment in those best available existing technologies. Another interesting study (Mabey and

[6] Edmonds and Wise (1997) in the MiniCAM model as an alternative to traditional tax or permit-based protocols examine a technology protocol based to a large extent on a menu of backstop technologies.

Nixon, 1997) compares a model with endogenous technical progress (diffusion) to a similar model, which however, include exogenous technological progress. Their conclusion is that the description of technological progress is not the most vital assumption. These two models are then compared to another model with different formulation of production structure. The description of production structure is found to result in a larger difference in outcome than the endogenous versus exogenous description of technological progress. Another conclusion is that general equilibrium-based models **without** endogenous technological progress tends to overstate the economic costs of energy policies based on carbon taxes.

Endogenising and explaining invention and innovation in energy and environmental technology are related to the theory of endogenous technological progress. The next section is devoted to approaches describing endogenous innovations in energy and environmental technology.

3. Innovation and long-term energy demand

For all long-term analyses of energy demand the issue of innovation will dominate the question of technological progress. At the same time the innovation issue is the most difficult to address by empirical economic modelling. Therefore, in many cases innovation has been treated as exogenous in empirical models of energy demand.

Innovation has implications for energy demand in different ways:

* Innovation of new energy supply technologies.
* Innovation of technologies that directly save energy (end-use technologies).
* Innovation of new production processes, intermediate inputs and organisations that indirectly affects the demand for energy.
* Innovation of new consumer products that change the consumption pattern and indirectly affects the energy demand for production.

Innovation of new energy technologies is a broad category of innovations of new fuels and low-cost equipment to take advantage of new fuels (hydrogen) etc. These can all be categorised as primary technologies that will improve the efficiency of converting fuels or using renewable energy resources. The element of a major technological breakthrough for a specific technology will be impossible to predict. On the other hand, the innovations that make an existing prototype technology economically viable are slightly easier to predict as these innovations are related to a large number of minor improvements, and these emerge more gradually in time. The argument could be that these improvements come mostly from applying results from the common pool of knowledge, and this knowledge pool evolves gradually. So here is one argument for using these constant efficiency improvement (AEEI) terms in energy-economy modelling.

The second innovation category refers to end use technologies. Here there is a distinction between the end-use technologies of firms and households that is important for modelling issues. Household members are not likely to undertake research or studies to improve energy efficiency. Maybe they are involved in search activities for collecting information to apply energy-saving technologies in their homes or when choosing between different brands of a household appliance. But these activities or the behaviour driving them can hardly be characterised as innovation and implemented in models.

When modelling innovation in end-use technologies the effort will be concentrated on corporate or public research activities. In most cases modelling has been applied in the past to the case of firm behaviour.

The overall technical progress also has implications for energy demand. There will be technical progress, which increases energy use, as well as technical progress, which decreases it. Technical progress could be related to production technologies, inventions in transportation etc. In most cases, automation requires the use of more electricity, in the same way that faster means of transport requires an increased use of various types of energy. In other cases, energy consumption will be reduced, e.g. when the use of industrial enzymes enables low-temperature processes or when the reorganising of a processing routine reduces the processing time and hereby also conserves lighting or room heating. Thus, energy efficiency could well depend on technological developments that have nothing to do with the direct aim of improving energy efficiency. This dependence means that no energy or environmental policy option exists for influencing this part of energy efficiency development.

The discussion of the overall technical progress effect on energy demand links to the old discussion of whether energy and capital are complementary or substitutes as production inputs. Both possibilities exist, but it is very unsettled which of the two possibilities is dominant.

The last innovation option is the most indirect technology influence. The innovation of new consumer products will change the pattern of consumption through time. Whether this change will give rise to more or less energy consumption is very unclear. In one case of household appliance modelling this has implications for the energy demand forecasts, as will be seen in the next section. Will innovation of new consumer products appear only in the form of products that consume very little energy or will there be continued innovation in the form of new electric appliances that consume a relatively greater amount of energy?

Innovation that is specifically concerned with energy technologies is the most relevant area to model if the aim is to analyse possible **policy instruments** that influence energy efficiency. Carraro and Galeotti (1997, 1998) describe a macroeconomic model for Europe called WARM, in which technological progress is endogenous. The WARM model is an econometric general equilibrium model estimated for twelve EU countries featuring imperfectly competitive markets, trade flows, structure of energy markets and the role of technological progress. The modellers see two channels through which environmental policy can influence technological progress and hereby energy efficiency.

- Publicly funded subsidies to firms R&D will lead to new energy savings and environmentally friendly technologies.
- An investment subsidy to firms committing to adopting the best available technologies will accelerate technical progress.

In the model there are two kinds of technological progress: first, the invention of new energy technologies and energy-saving innovation created by corporate R&D, and secondly, the diffusion of existing best available technologies. The endogenous technological progress has been analysed in many theoretical models but the WARM model has the advantage that the technology representation is empirically founded. The quantified relation between R&D and technological progress distinguishes this model from those that describe technology diffusion alone.

In the model firms R&D is endogenously determined by prices, output and policy variables as environmental taxes or R&D subsidies. R&D activities by firms affect the composition of their capital stock.

The ratio $\mathbf{k_e/k_p}$ of the stock of the environmental friendly capital (energy-extensive) to the standard polluting capital (energy-intensive) is used as the indicator of technological progress. R&D spending increases the growth of the energy-saving capital stock $\mathbf{k_e}$.

The argument for providing the subsidy to R&D activities is based on an assumption of positive externalities of R&D activities by firms, which lead firms to under-invest in R&D. Taxes or permits, on the other hand, could be suboptimal instruments for achieving the right level of technological progress.[7] Carraro and Galeotti argue that a policy mix of subsidies to environmentally friendly R&D along with taxes to increase the adoption of energy-saving technologies should be considered. Through such a policy it seems possible for the economy to follow a growth path without environmental harm as the four simulation scenarios in their paper show. In their argumentation for the use of a combination of policy instruments the authors are in line with Goulder and Schneider (1997), who examine the combination of carbon taxes and R&D subsidies (see below).

The WARM model is outstanding in two ways: First, it includes explanations for both diffusion of technologies and innovation. Secondly, the relationship is empirically based upon data for a number of countries. The model can be criticised in that by concentrating on policy issues alone, it explains only one part of technological progress, namely the part that most obviously can be influenced by policies. Most of the progress in energy efficiency does not relate to a choice between energy-efficient or non-efficient capital. Energy-efficiency is often a by-product of investments to increase efficiency of other inputs, for example, processing time or the size of components and hereby materials inputs and assembling time (labour). But even when energy constitutes only a minor fraction of production costs, subsidies could work if the technologies despite their differing energy efficiencies do not differ with respect to their other main characteristics. The description of technological progress in the WARM model covers only energy technologies. The overall technology progress that is not included in WARM will have a considerable impact on energy efficiency improvement.

The critique formulated by Kemp (1997, p.40) that "the innovator gains usually result from the sale of the new technology rather than from lower abatement costs for the innovator" also applies to the WARM modelling approach.

Other European models, namely the PRIMES energy-systems model (European Commission, 1995a) and the E3ME[8] model (European Commission, 1995b) are currently being developed to cover some types of innovation in ways similar to that of Carraro and Galeotti. The E3ME model already includes a description of technological progress by using the cumulative investment (including investment in R&D) to construct an indicator of technological progress for the 32 sectors and 14 regions of that model.

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[7] Carraro and Siniscalco (1994) include a thorough discussion of the optimal policy choice between environmental taxes (permits) and investment subsidies to foster adoption of existing cleaner technologies.

[8] Energy-Environment-Economy Model for Europe is a macroeconometric model developed by an inter-European model team with support from the Joule II Programme and co-ordinated by Cambridge Econometrics.

However, this description is for describing technological progress, and not for progress in energy efficiency. Innovation policies directed toward increasing energy efficiency can be evaluated only on their short-term effects on total demand and on the long-term effect on overall productivity. Currently work is carried out to describe with greater precision the innovation processes and links between R&D, patents and energy efficiency in E3ME. In the PRIMES model work is concentrated on introducing real learning curves for specific energy technologies.

Grubler and Messner (1998) incorporate learning in a model based on a bottom-up energy systems model with intertemporal optimisation. They examine learning mainly for electricity-producing technologies, but include both learning from demonstration and from R&D and not only as a function of cumulative investments. When analysing emission trajectories and the question of timing they find, partly in opposition to Wigley et al (1996), that it is important to undertake activities now to stimulate learning.

Also Schneider and Goulder (1997) examine R&D policies in a large-scale general equilibrium model including incentives to invest in R&D. They also examine knowledge spill-overs and R&D market functioning. They find a combination of a carbon tax and a broad R&D subsidy to be less costly than a carbon tax alone to achieve a given 15% reduction of CO_2 emissions. This result is based on R&D spill-overs; if the spill-overs are large and benefit industries other than those which are energy related, the subsidy will increase in importance in order to overcome the R&D market failure.

Dowlatabadi (1998) includes endogenous progress not only for increasing energy efficiency in conversion and end-uses, but also endogenous efficiency in the discovery and recovery of oil and gas. He uses an integrated assessment model ICAM-3 with simple endogenisation of technological progress to analyse the sensitivity of mitigation cost estimates. His findings point to the effect of technological progress in reducing the cost of energy consumption. He finds that emissions from business as usual are higher than otherwise expected if technological progress is endogenous. Thus, additional reduction is needed to meet a given CO_2 concentration target, but the costs will also be lower than traditional estimates.

Kemp (1997) surveys a number of theoretical models of firm incentives to innovate in pollution control. Of these models, the study by Milliman and Prince (1989) seems the most elaborated with respect to comparing incentives for both innovation and diffusion under five different regulating regimes. This study considers incentives both for polluting firms and for outside innovators. Innovation seems least favourable for firms under direct regulation, whereas the other four regulating regimes: emission subsidies, free permits, auctioned permits and emission taxes produce equal incentives. Direct regulation does not include the option for the firm to collect the gains from reducing its own pollution, when its marginal abatement costs are reduced by the innovation. The abatement cost reduction only has effect on the amount of abatement prescribed in the direct regulation. The study summarises incentives over the entire process of technological progress of innovation and diffusion including optimal agency response to the change in marginal abatement costs induced by the innovation and the diffusion process. For non-patented discoveries an innovator is found certain to benefit only under auctioned permits and emission tax regimes, whereas the outcome in the other regulating regimes is uncertain.

An important assumption in the Milliman and Prince analysis is a downward shift in the entire marginal abatement cost curve as a result of an innovation. A reduction in abatement costs only for an interval of pollution, for example abatement below some level of effort, would complicate the analysis and could eventually result in direct control inducing the same incentive to innovate as the regulatory regimes with economic instruments.

Laffont and Tirole (1993; 1994) analyse incentives for environmental innovation under different regimes of environmental regulation. Under a pollution permits system the socially optimal permits price will be driven down close to the marginal costs of supplying a new technology (license). But this leaves no incentive for the innovator to undertake R&D in the first place. Laffont and Tirole instead examine another system where ex post licensing of the innovation takes place by the government, which then redistributes the innovation to the polluters. The authors find that such a system leaves the innovator better off and provides a greater incentive to innovate.

Ulph (1997) surveys a number of recent studies based on a game theoretical approach to the decision of firms to invest in R&D. He considers two different ways to model possible R&D paths: (a) non-tournament models with more than one R&D path leading to innovations that are capable of producing the same final product, and (b) tournament models with just one possible innovation capable of producing a specific final product. All firms in the second case compete to make this innovation and have it patented. Ulph finds that environmental policy in the case of taxes will stimulate R&D in non-tournament models, whereas the effect in tournament models will depend on competition in product markets.

Carraro and Soubeyran (1997) examine corporate strategy responses to environmental taxes in a game theoretical setting. They find that within a given industry firms with identical technologies might respond differently to an environmental policy. Some firms co-operate in carrying out R&D, others relocate production and some decide to imitate the innovations that the first group comes up with. The assumption of fixed costs in R&D is the reason that a coalition of identical firms is formed to co-operate in carrying out R&D. At some point the reduction of R&D costs to the individual member of the R&D coalition from including another firm become small. The price of a licence for the use of the innovation from the coalition also decreases with the number participating in the coalition and the number of firms relocating production to abroad. Correspondingly the number of firms in the coalition decreases with the price of a license. Production abroad is assumed to be connected with transport costs and cost incurred as a consequence of trade barriers. An equilibrium with some firms relocating, some buying a license or imitating the innovation and some co-operating in R&D to make innovation is found. This result is dependent on the assumptions, for example, will too high foreign profits lead all firms to relocate and too high efficiency in R&D from an additional member of the R&D coalition will lead all firms to join the coalition and no firm will relocate.

Goulder and Mathai (1998) develop a number of analytical results for optimal carbon tax profiles under various assumptions of the characteristics of technological progress. They consider R&D activities and knowledge accumulation as well as learning by doing accumulation of knowledge. For a carbon tax their general result is a lower optimal carbon tax with the existence of induced technological progress. Their findings also suggest that the presence of induced technological progress from R&D investment justifies the shift of some abatement from the present to the future, whereas induced technological progress from learning leads to ambiguous results.

Ausubel (1995) points to the long-term trends for improving the efficiency of different kinds of equipment. Why should an observed trend of decreasing carbon intensity in electricity production be reversed in the future? His remark raises the question of a possible difference between the improvement of efficiency for a specific technology and the improvement in aggregated efficiency caused by the innovation and introduction of new technologies. Is there a decrease in the marginal innovation product of putting more and more R&D into the development of a specific technology, but not in the innovation of **new** technologies?

Beside these relatively applied modelling approaches the endogenous growth theories have explicitly addressed the question of explaining innovation. The underlying theme of this is to explain the technological progress that seems to account for almost one-half of the long-term growth in per capita income. This is very similar to the attempts to explain the progress in energy efficiency (AEEI), which is especially important in the long-term.

Endogenous technological progress in relation to environmental economics theory has been explored in recent years. Starting from endogenous growth theory, researchers have been introducing renewable and exhaustible resources, examined balanced growth, market imperfections and sustainability issues. A central issue has been whether technological progress could secure the necessary improvement in efficiency of the use of non-renewable resources to sustain balanced growth.

Another approach has been to look at the possibility for technical progress to secure that environmental pressure is kept at a level consistent with the regeneration of natural capital. Bovenberg and Smulders (1995) in a two-sector endogenous growth model with constant returns to scale examine the possibility of permanent growth with a sustainable level of environmental pressure from pollution. They find that if the optimal choices of agents increase both physical and human capital then the technological progress produced in the knowledge sector increases the productivity of pollution and decreases the pollution/final good output ratio, whereby permanent growth can be sustained.

In other endogenous growth models the mechanism works through the number of varieties of capital equipment with the R&D sector producing new varieties with constant returns to scale.[9] The new varieties differ also with respect to the environmental pressure (emissions ratios) and hereby the environmental pressure can be reduced at a steady rate.

Schou (1996) also examine a model with different varieties of capital that differ with respect to their ability to substitute a non-renewable resource as an input in the production of basic goods. The R&D sector produces knowledge that is used in the production of capital goods. He finds that the growth might be in-optimal low in the market solution based on the imperfections in the R&D and capital sectors. Buyers of patents are assumed to be monopolists and the price of the capital varieties will be too high. The too low growth will not necessarily be accompanied with a lower extraction of the non-renewable resource than in the optimal solution.

Beltratti (1997) surveys a number of growth models developed for analyses of environmental problems. He includes both traditional and endogenous growth models. From all these analytical models there are implications for the relation between technological progress and long-term energy demand. Permanent growth is dependent

[9] Carraro (1998) and Beltratti (1997) discuss some of these models.

on the progress of energy technology with respect to both the efficiency of use of non-renewable energy and the environmental pressure from its use. Energy could be interpreted as the input to production, which in different endogenous growth models is considered as either a non-renewable resource or merely a source of pollution. Those models where growth is driven by R&D producing new varieties of capital goods could maybe be used in the case of energy. But possibly the description of these new varieties with respect to their energy consumption per output unit is too abstract to be included in the empirical energy-economy model.

The discussion of innovation and the attempts to incorporate an improved explanation for technical progress in the energy-economic models will continue, but it should not be expected that in doing so the success achieved will be more pronounced in the energy field than in the field of overall technological progress. Nevertheless, the possibility exists that the long existing policy tradition of public financing of energy research could provide empirical insight to the innovation results of this financing.

An empirical puzzle is the conclusion drawn by Hogan and Jorgenson (1991), who analyse another aspect of technological change. They state that the effect of higher energy prices through fuel taxes with the objective of reducing CO_2 emissions could impact not only the rate of technical change in energy technologies but also the general productivity. They find that technology change has been negatively related to energy prices. If energy prices were to increase the rate of productivity growth would decline. Thus, indirectly a tax policy to induce technological innovation in energy efficiency could have a negative feedback effect on the economy through lower general productivity growth.

4. Model projections of energy demand with different descriptions of technological progress

The different approaches to modelling energy efficiency developments affect the long-term energy demand that the models project. The importance of the modelling approach relative to the specific assumptions about energy efficiency is an issue that need to be explored further. The widely accepted point that the modelling of technological progress is among the most important reasons for different model results[10] often neglect to specify whether it is the model approach itself or the efficiency assumptions made in specific projections that is the main difference. Hourcade and Robinson (1996) argues that it is not the different modelling approaches but the actual assumptions put into the models that is causing different results in the studies of greenhouse gas mitigation costs.

In this section two different Danish models illustrate two different approaches and assumptions and their consequences for energy demand projections. The comparisons and sensitivity studies referred in the above sections (Mabey and Nixon, 1997) and (Dowlatabadi, 1998) are comparing macroeconomic models, whereas a macroeconomic model description are compared to bottom-up vintage models here.

Vintage models do describe the aggregated efficiency developments including the restrictions from the efficiency of past capital vintages. In the long run the vintage effect on average efficiency becomes less important and the annual efficiency improvement will be more stable. Such a development will occur if the forces driving investment in new capital vintages follows increasingly stable growth rates. In long-term model

[10] Carraro and Galeotti (1997)

projections the capital vintages will only be of different size as a result of historical fluctuations in vintage size. If a given vintage is assumed to have a lifetime distributed around some mean, then the vintage effect will become less important in time.

The model of electric appliances applied here is mainly a mechanic description of technology **diffusion** based on assumed efficiency improvements for a number of specific appliances. The vintage model does not include a description of innovation of new electricity consuming appliances. This limitation of the model can be just as important for long-term energy demand as assumptions about efficiency improvement for existing appliances. This possibility is examined below, where a consumption component in the macroeconometric model of Denmark ADAM[11] and Danish vintage models for electric appliances and residential heating are compared with respect to long-term energy demand projections.[12] It is examined whether the different assumptions made about technological progress are responsible for the differences in the energy demand projections that are obtained.

To compare the two models, the specific description of technological progress must be examined. Furthermore, the underlying assumptions of the rate of progress must be quantified to compare simulation results with the two models.

A possible representation of technological progress in a macroeconomic specification of residential energy demand for electricity could, for example, be

$$E = e(p_e / AEEI, p_j / AEEI, C^E) \qquad (1)$$

E	Electricity demand
p_e	Price of electricity
pj	Price of other residential energy demand components
$AEEI$	Autonomous electricity efficiency improvement (indexed)
C^E	Total residential energy consumption

The AEEI representation in residential electricity demand accounts for an efficiency improvement through diffusion of more efficient appliances when old appliances are replaced as well as the innovation of more efficient versions of the existing appliances. As electricity demand is modelled at the aggregated level, this specification of technological progress also includes new types of appliances and possible efficiency effects from a change in the composition of the total stock of electric appliances.

However, ADAM does not include any explicit assumptions of efficiency, but the income elasticity of this component of private consumption is low 0.94 compared to 1.75 for durable goods. It is possible that the low income elasticity is caused partly by embedded technological progress, as income increases tend to accelerate the replacement of electric appliances, which again increases the average efficiency of the stock of appliances. Another explanation can be that income and technological progress follow similar time trends. The different income elasticities are reflected by comparing the average growth rate 1985-2020 for electricity and heating 0.53% in the ADAM projection shown in Figure 1, with the average growth of total private consumption

[11] Annual Danish Aggregated Model

[12] The vintage model of electric appliances and the model of residential heating demand are documented in Jacobsen et al. (1996). These two models are also included in the analysis of integrated bottom-up and top-down models (Jacobsen, 1998).

2.29%. Another explanation for the slower growth of this component is a real increase in the consumer price of electricity and heating in combination with the long-term price elasticity in ADAM, which is –0.89. The high long-term price elasticity could be supposed to relate to price-induced technological progress as part of the long-term price response.

Three projections for energy demand are included in Figure 1. All three projections imply low growth rates for this component of private consumption. The ADAM projection is an annual growth of 0.7% from 1995-2020 compared to 2.6% annual growth for total private consumption in the same period. The slow growth of energy demand in the ADAM projection is a result of a low income-elasticity for this consumption component in combination with steadily rising real energy prices until 2015.

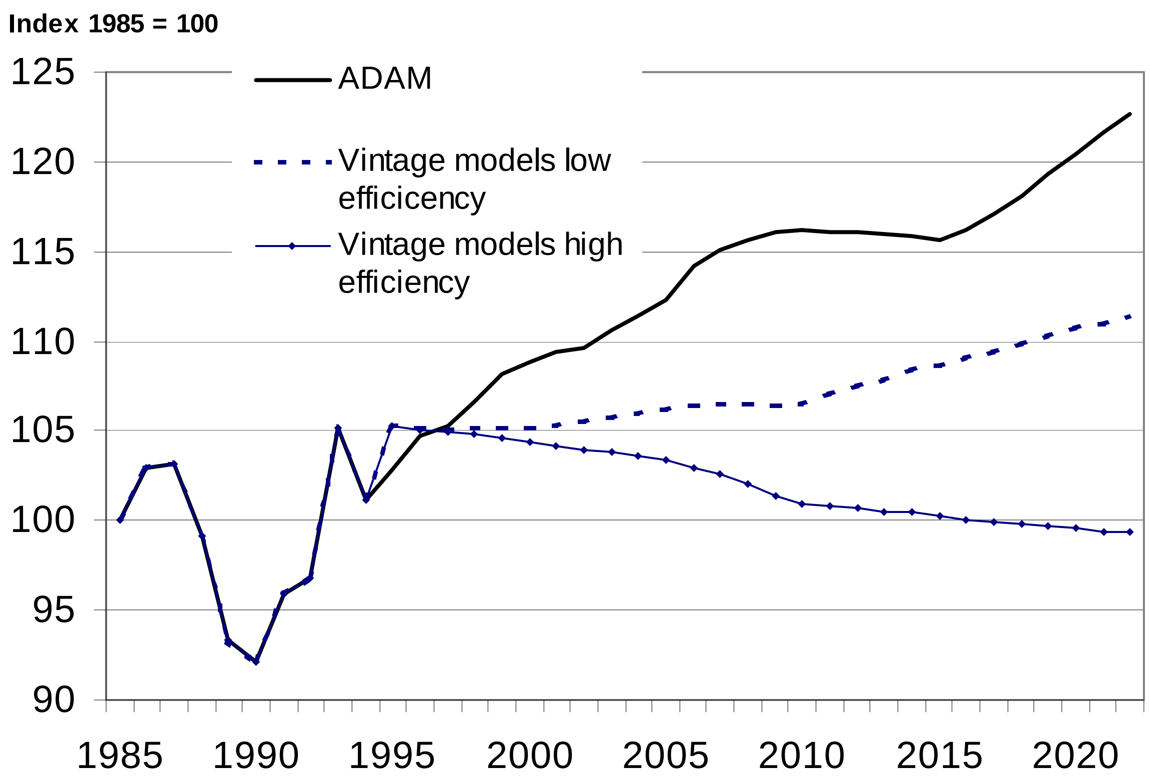

Figure 1 Residential demand for electricity and heating

The projection in the vintage models with low efficiency assumptions is an even slower growth in demand. Low efficiency assumptions means no efficiency improvement for the new vintages of electric appliances and no improvement in average local efficiency for heating technologies from 1995 an onwards. Average efficiency for electric appliances increases until 2004, when most of the stock of appliances existing in 1995 has been replaced. The high-efficiency projection assumes annual increases in efficiency of 2.5% for new vintages of the six most important appliances accounting for close to half of residential electricity demand. The weighted annual efficiency increase for all categories of electric appliances over the period 1995 to 2020 is only 1.25%, which is not an unreasonable high efficiency improvement. The assumption for heating demand is also around 1.5%. These high-efficiency assumptions result in a small decrease in the projected residential energy demand.

The model projections of residential electricity and heating demand differ very much. The long run difference is close to 25% higher energy demand in the ADAM projection compared to the high-efficiency projection of the vintage models. The driving factors in the vintage model: housing area, population, and consumption of durable goods are the variables determined in ADAM, which ensure that the use of macroeconomic assumptions and the projected macroeconomic variables are consistent between the two types of models. The important question is whether it is the description of technological progress or the assumptions that are the main explanation for the different projections.

Electricity demand for appliances is modelled with vintages of appliances where each new vintage is improved with respect to electricity consumption. The efficiency development for the electric appliances is specific for the individual appliance, but a weighed average of the 16 categories of appliances constituting residential electricity demand in the vintage model can be constructed. With weights of projected energy demand stated by category for 2020 the average annual efficiency improvement 1985-2020 is 0.5% in the low efficiency projection and 1.1% in the high-efficiency projection. The 1.1% is not an unreasonably high efficiency improvement, but the importance of this assumption is seen in that energy demand is 13% higher for the projection where average efficiency improvement for electric appliances is reduced to 0.5% annually. Different assumptions in the vintage model thus create projections that differ just as much as the projection in ADAM and the low-efficiency vintage projection differ.

Just as Hourcade and Robinson argue the different efficiency assumptions in the vintage models (bottom-up) are an important reason for differences in energy demand projections. The vintage approach to modelling technological progress even when no efficiency progress is assumed for **new vintages** includes a vintage efficiency effect. For the first ten years of the low-efficiency projection the vintage projection imply slower demand growth than the ADAM projection. From 2010 when the stock of appliances existing in 1995 has been replaced the two projections of demand grows with nearly the same rates. The vintage modelling approach for technological progress is thus found to have important implications for demand projections in the medium term, which in the long-term is reduced to an accumulated impact on the level of demand.

Another explanation for the difference between the vintage model projection and the ADAM projection and a major point of criticism of vintage models for appliances arise from the category designated "other appliances". This category was relatively small around 1995, the outset of the projection period, but how does this category evolve in the projection? In our case no link to economic activity exists for the category and the category indeed remains small. Contrary to this it would be expected that in the long-term the growing economy would increase the number of appliance categories that have significant electricity consumption, including some technologies not even existing today. This is a property of the applied model of electric appliances just as important for the difference between the projections as the actually applied rate of technological progress, and the importance increases as the horizon of analysis is expanded.

It is possible to use the bottom-up model to create an aggregate for energy efficiency that can be used in the macroeconomic specification. This is done in Andersen and Trier (1995), where an adjusted version of the ADAM relation for residential electricity demand includes a trend for efficiency taken from an aggregation of forecasts for appliance efficiencies. Household demand is for services from appliances, which means that it is the efficiency-adjusted electricity demand that enters into the estimation. This is the most obvious way to solve the explained problem with this other appliance category, at least if you are a macroeconomic modeller. Another option is to put more effort in improving the description of the economic driving forces for the category of other appliances. This include a better description of the energy efficiency improvement as this category at the outset of the projection include only appliances which use very little electricity, but this cannot be expected to continue for a long-term projection period.

To compare the result with the macroeconomic determination of residential electricity and heating demand, the efficiency in space heating must also be examined. Residential heating is described in a model including different local heating technologies applied at the residential level. The local effectiveness and share of these technologies are projected. Residential demand for heating is determined by combining the effectiveness with the housing area and parameters for climate and desired room temperature.

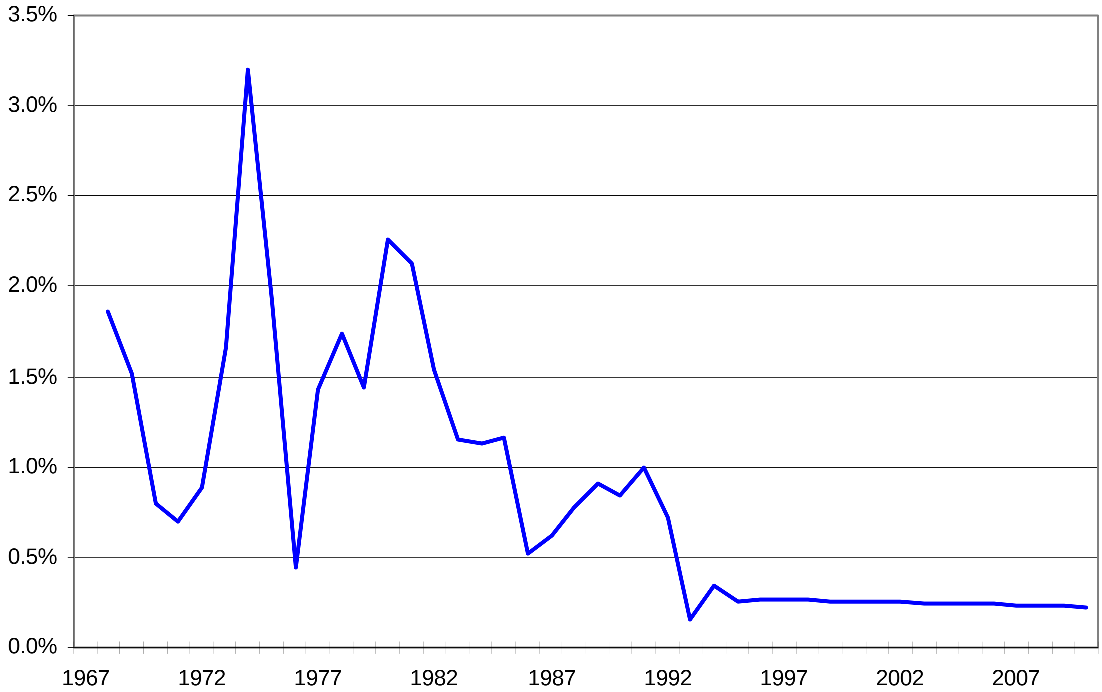

Figure 2 Annual increase in local efficiency for an aggregate of six heating technologies

The figure shows historically large variations in the annual improvement in efficiency. This is seen even though the figure shows two-year moving averages of efficiency increases with efficiency weighted by the share of the heating technologies. In the projection the efficiency follows a steady improvement but with much lower annual increases than historically. There are many arguments for a slower efficiency improvement, among which the composition argument is most important. The change from local oil-based heating technologies towards district heating, accounting for a share of around 50% of households heating technology today, will not proceed at the same speed. Even for the local efficiency the oil burners will probably be only marginally more efficient than the 70% level that exists today. The projection of an efficiency increase of around 0.25% annually is very moderate and even if it is combined with the assumption of an annual decrease of 1% in the heating demand per square meter as a result of improved insulation etc. the combined assumption lies within reasonable limits.

Another issue for comparing energy demand projections from models based on different approaches, and of equal importance, is the difference of policy effects among the approaches. In some models, long-term energy demand can be affected only by either exogenous price changes or taxes. In other models, a range of policy instruments can influence the efficiency developments. In the models mentioned above, the policy instruments are very different. In ADAM the policy instrument is to increase energy taxes for households. In the vintage model, taxes also have an impact on the intensity of use for some of the appliances, but their effect is limited. Due to its detail, the vintage model includes a number of policy instruments.

- Electricity tax
- Standards for new vintages for each of the 16 appliance categories
- Indirectly through taxes on the purchase of durable goods

The effect of the electricity tax is rather moderate compared to the effect in ADAM and the effect only works through intensity of use. There is no effect on the volume of new purchases, nor on the choice between brands of appliances with different efficiencies. Thus, there is no effect on the composition of vintages with different efficiencies and the effect on aggregate efficiency is small as only some of the appliance categories have price elasticities for intensity of use, and the elasticities are quite small, around -0.1.

Standards constitute a direct regulation on the maximum electricity consumption for a vintage of a specific appliance. Through the replacement of old vintages and the modelled increase in coverage, standards affect the average efficiency improvement and the long-term electricity demand.

The last policy variable works through taxing the purchase of durable goods. The ADAM consumption group has a very high income-elasticity and a long-term price-elasticity of –1.52. The consumption group, through a link to the vintage model, affects the rate at which coverage increases by using an estimated relation between the consumption of durable goods and the purchase of each category of appliance. The volume of vintages of different appliances is affected, but the level of saturation (the maximum coverage percentage of households in possession of a given appliance) is unaffected. Thus, the impact on electricity demand is of a temporary nature and works through the stock of appliances and the average efficiency of the stock.

In the vintage model, policy options influence energy demand in three ways: through a change in the intensity of use, the stock of appliances and the average efficiency of the stock. Among the policy options, standards are the most powerful one and this policy works through the diffusion rate for the least electricity-consuming brands of an appliance. In these models nothing is said about innovation, but it is often argued that a gradual tightening of standards will force the producers with the least efficient appliance to develop new models that meet the standards. Following this, producers with efficient appliances will have to develop even more efficient products to diversify their brand from other producers. There is one important problem in this argument for innovation effects. It is the unlikeliness of the small Danish market to be of any importance for the producers of electric appliances. Therefore, tightened standards in Denmark cannot be expected to result in any innovations of more energy-efficient electric appliances.

5. Concluding remarks

Energy demand modelling includes a variety of approaches to describe technological progress. Technological progress at the same time is also a key issue for modelling long-term energy demand and for evaluating possible policy strategies to reduce the environmental impacts of energy use.

Technological progress has been modelled as an exogenous improvement in the energy efficiency or at the other extreme as endogenously determined by the R&D effort, prices, taxes and market structures. For long-term energy demand the issue of innovation of new technologies will become more important than the diffusion of already existing technologies. Innovation has been modelled mainly in an analytical context, but recent examples of innovation in empirical models exist.

New economic theoretical research in the field of endogenous growth and industrial organisation has been applied to environmental economics and hereby to energy issues. This has brought new insight to the question of incentives of firms to engage in R&D activities and hereby their effort to reduce long-term energy demand. Growth theory has examined the possibility for having permanent economic growth without the same growth in energy demand or energy-related pollution, but the conclusions are still vague and dependent on the model specifications.

The endogenous innovation induced by endogenous R&D effort has been implemented in a number of empirical models, where the WARM model, the model of Schneider and Goulder (1997) and the model by Dowlatabadi (1998) are the most interesting examples. Macroeconomic energy-economy models have a very aggregated and generalised description of the change in energy technologies. It is possible to endogenise technological progress at the aggregated level, but it is very difficult to establish empirical results to verify the endogenisation. Another approach is to emphasise a disaggregated description of existing technologies and those technologies which are at a promising development stage. This excludes the description of innovation, but it improves the description of existing technologies and makes it easier to evaluate the assumed efficiency improvements at this level.

Long-term energy demand in Danish models can be compared with respect to the significance of the description and assumptions made about technological progress. Vintage models of electric appliances and residential heating result in energy demand forecasts that differ from a forecast with a macroeconometric model ADAM. The ADAM demand relation does not explicitly include efficiency, but involves an income-elasticity less than unity. The vintage model includes efficiency assumptions for all new vintages for 16 categories of electric appliances and describes the **diffusion** of efficiency improvements. These assumptions are important for the projection of energy demand.

The difference in long-term energy demand between two vintage projections with low and high efficiency assumptions is of the same size as the difference between the low-efficiency vintage projection and ADAM demand projection. Vintage modelling imply a time delay in efficiency developments. The low-efficiency projection in the long run has nearly the same growth of energy demand as the ADAM projection, but the first 10-15 years of diffusion of the 1995 technology has contributed to an accumulated difference versus the ADAM projected long-term level of demand. Therefore it is both the vintage modelling approach and the specific assumptions in the vintage model that are important explanations for the different projections.

Another explanation for the difference between the vintage model projection and the ADAM projection is the lack of innovation of new electricity consuming appliances in the vintage model. In the long run this property tends to moderate the growth of electricity demand. The vintage model of electric appliances gives no explanation for new appliances and the economic driving forces for this category of other appliances. The conclusion is that a vintage model of electric appliances, even if it includes linkages to economic activity and income, should only be applied in the long run if it includes an appropriate description of the group of new electric appliances.

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Technology diffusion in energy-economy models: The case of Danish vintage models*

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department, PO. Box 49, 4000 Roskilde, Denmark
email: henrik.jacobsen@risoe.dk

Abstract

Technological progress is a very important issue in long-term energy demand projections and in environmental analyses. Different assumptions on technological progress and diffusion of new technologies are one of the reasons for the very diverging results, which have been obtained using bottom-up and top-down models for analysing the costs of greenhouse gas mitigation. This paper examines the effect on aggregate energy efficiency of using technological vintage models to describe technology diffusion. The focus is on short- to medium term issues.

Three different models of Danish energy supply and energy demand are used to illustrate the consequences of the vintage modelling approach. The fluctuating utilisation rates for power capacity in Denmark are found to have a significant impact on average fuel efficiencies. Diffusion of electric appliances is linked to economic activity and saturation levels for each appliance. In the sector of residential heat demand fuel price increases are found to accelerate diffusion by increasing replacement rates for heating equipment.

1. Introduction

Technological progress is an important issue in both energy and environmental analyses that have a horizon of more than just a few years[1]. In the long run the innovation of new technologies and improvements of existing technologies will be the dominant explanation for the technological progress and efficiency improvement. However, in the short and even in the medium term diffusion of existing technologies can have a substantial impact on the rate of efficiency improvement. Vintage models do include technology diffusion and hereby they are capable of describing efficiency improvement. The focus in this paper is the importance of technology diffusion in a short- to medium term context.

In energy-economy models the energy efficiency improvement is often exogenous and constant and is represented by the concept AEEI[2] (Autonomous Energy Efficiency Improvement). Models that address the question of innovation and diffusion also exist[3].

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[1] Toman (1998,) finds that "it is widely agreed that technical innovation is the ultimate key to successful global measures to stabilise the concentration of GHGs in the atmosphere"

[2] The IPCC (1996) report section 4.4.3. among other issues discusses the use of AEEI. Many of the models applied for global greenhouse gas mitigation analyses use this representation for technological progress Global 2100: (Manne and Richels, 1992), GEM-E3: (Conrad and Schmidt, 1998), GREEN: (Burniaux et. al., 1992).

[3] Dowlatabadi (1998), Carraro and Galeotti (1997), Mabey and Nixon (1997), Schneider and Goulder (1997).

The use of a constant AEEI[4] can be criticised especially in short- to medium-term analyses with a horizon of less than 50 years where energy efficiency will depend on a variety of factors as capacity utilisation, vintage effects from new investments, public policy and implementation of already known technologies. A detailed description of energy technologies could improve and qualify a top-down (macroeconomic) description of energy efficiency developments based on AEEI[5]. Examples of using vintage models for the description of the development in aggregate energy efficiency will be presented in this paper.

Bottom-up or technical vintage models do not explain innovations, but these models do describe technologies in detail that are not yet fully developed for commercialisation.[6] By the dependence on fuel prices, regulation and investment activity, the aggregate energy efficiency is described with a kind of endogenous implementation of technologies and technological diffusion but it cannot be characterised as endogenous technological development.

Diffusion of energy technologies can be seen from a very detailed perspective of a specific technology or equipment, which is the approach that characterises bottom-up models. This detailed description of improvement can be the basis for an aggregated measure of energy efficiency development. In this context it is important to distinguish between two different aspects of explanation for aggregate energy efficiency developments. One aspect is the aggregation of specific technological forecasts and diffusion projections and another aspect is explaining the diffusion process.

This paper discusses both aspects by using models with a lot of detail that has important links to driving economic factors. Short-term demand changes through the fluctuating utilisation rates for power capacity in Denmark are found to have a significant impact on average fuel efficiencies. The vintage model of electric appliances shows that economic growth has relatively little impact on diffusion and efficiency developments for the stock of a specific electric appliance. In the sector of residential heat demand fuel price increases are found to accelerate diffusion by increasing replacement rates for heating equipment.

The first part of this paper discusses different approaches to describing diffusion of technologies. In the second part the examples from Danish vintage models illustrate what this approach adds to the description and explanation of changes in energy technologies and efficiencies.

2. Diffusion of technology

The issue of technology diffusion is important for energy efficiency and in a wider context the climate debate with respect to "no regret" options for greenhouse gas mitigation and the efficiency gap. Toman (1998) based on IPCC (1996) and others discuss the energy efficiency gap as mainly related to market imperfections. There are other explanations for the efficiency gap, for example, the existence of preferences for other

[4] Dowlatabadi (1998) , p. 483 criticises the ability of a constant AEEI to replicate US historical energy intensity figures. Carraro and Hourcade (1998) argue that many of the existing models (see note 2) does not provide an endogenous representation of technological change which is a crucial limitation of those models.

[5] An example can be found in Møller Andersen and Trier (1995)

[6] The LEAP model in an accounting framework (Heaps, 1995) include some vintage characteristics in the determination of end-use energy demand and for biomass supply, but the model does not keep track of all vintages of a given device. Instead the "energy intensity" of a given device is projected, for example, depending on developments related to the change in stock or coverage.

characteristics than energy consumption, the existence of transaction costs, search costs etc. The imperfections can be public regulation affecting the technology choice[7], credit rationing or missing markets for energy component of production technologies. The imperfections result in too slow technology diffusion and removing the imperfections and other barriers[8] can speed up the diffusion process. Vintage models can be used to analyse possible policies for increasing the speed of diffusion.

Technology diffusion can be characterised in different ways. One aspect is the diffusion of process technologies measured as the share of production produced by a specific technology. Another aspect is the diffusion of a new product measured as the volume of production of this product or the market share.

Kemp (1997) reviews a number of technology diffusion models. The models are divided into epidemic models with or without economic factors and rational choice diffusion models. The epidemic model is based on an assumption of a learning process or a change in taste as information is spreading. One of the descriptions of epidemic models is a logistic model but also the Gompertz model and the Bass model have been applied to modelling technological diffusion. A major problem with the epidemic model is that it does not address the question of why the speed of diffusion differs between different analysed technologies and why some firms or consumers adopt more quickly than others do. Rational choice or discrete choice models build more intensively on economic consideration by adopting agents. Some versions of rational choice models considered as threshold models build on some critical variate to exceed a threshold level. Among those models are the probit and logit models and vintage models in some cases.

In comparing epidemic, threshold and vintage models of technology diffusion Kemp argues that different models are appropriate depending on the size of the population of adopters and the characteristics of the innovation in focus.

Diffusion of a product or process technology could alternatively be defined based on the number of producers of a new product relative to the number of potential producers in a specific branch of industry. Diffusion according to this definition is examined in an empirical study by Gottinger (1987). In this study a model of technology diffusion has been estimated for 8 products based on US data. The importance of market structure and several other factors was examined. Gottinger (1987) finds that the most important factor explaining the speed of diffusion is the "demonstration effect". This effect is a measure of the number of producers out of potential producers that adopt a new product or a new production technology. If the majority of new producers are insiders (producers already in the industry as opposed to outside producers expanding production activities to new areas or newly established producers) the diffusion process will be faster. Gottinger examines technology diffusion of mainly new final products. For new energy technologies there will be some similarities but also some differences to his findings.

In many cases different technologies are present in the market at the same time. To explain this it is important to distinguish between the case of different technologies used in production and the case of investment in different technologies at the same time[9]. In

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[7] Favourising technology that uses domestic fuel reserves with high cost or domestically produced technology.

[8] Decreasing transaction costs, for example by providing public information that compares the variants of a given appliance on the market.

[9] Clarke and Edmonds (1993) explain this by other cost characteristics - not only the costs associated with the specific technology but e.g. geographical (transport), labour qualifications etc. determine the choice of technology. Another example in the market for electric appliances is the co-existence of a

the first case different technology embodied in different capital vintages is important and vintage models can contribute to the quantification of this effect.

3. Vintage models and technology diffusion

Technology diffusion is an aspect of vintage models that is important for energy supply and demand analysis. There are different aspects of this diffusion

- Technical exogenous explanation for the size of new vintages
- Economic explanation for the replacement of existing capital stock
- Demand driven expansion of capacity

Meijers (1994) examines diffusion of technologies in a vintage framework. It is not energy technologies that are in focus in this work, but technology diffusion in general. He finds that vintage models have considerable advantages compared to aggregate production function models. In particular the introduction of, and the distinction between, embodied and unembodied technological change is modelled. Models on diffusion of new technologies show that the introduction of technologies takes a considerable amount of time. This is in contrast with traditional macroeconomic vintage models, where all firms invest in the same latest capital vintage. Firms within an industry probably make different decisions about their investment activity but all of their investment is assumed to be in the same technology.

Vintage models of capital with different energy efficiency

Vintage models of capital in all sectors of the economy can include energy characteristics for each vintage. Empirically it is difficult to distinguish between embodied and unembodied technical changes. The embodied technical changes are related to the energy efficiency of a vintage of capital.

Energy efficiency is seen as embodied in the new capital vintages. Berndt et. al. (1993) examine the empirical evidence of embodied and unembodied technological change. They find that the former accounts for only a modest share of overall productivity growth. The importance of vintages of capital and the impact on average energy efficiency thus seem to be quite small. Their study examined the aggregated manufacturing sector. If focus instead were on a specific capital intensive industry with identifiable technologies the vintage effect might be more important. The effect of changing capacity utilisation rates might blur the picture of new vintages. High capacity utilisation could result in lower average efficiency if the effect from using less efficient machines/capital equipment dominate. If instead high capacity utilisation means running the same machine for more hours the average per unit of output energy consumption might fall as upstart energy consumption decline in importance.[10] If the effect of increased use of less efficient machines dominate it could even offset the effect of increased investments, which will probably be higher at periods of high capacity utilisation.

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range of brands and product variants that can hardly be distinguished with respect to their main output.

[10] In the model of electricity production applied in this paper the first case of decrease in average efficiency dominate, but for most other sectors high capacity utilisation will probably mean running evening or night shifts.

Because energy inputs in most industries will be of minor importance relative to other inputs the energy consumption will be related to only a small part of the capital vintage. It is only a minor fraction of a capital vintage that has implications for energy consumption. In many cases energy efficiency will change with the replacement of specific equipment, which only constitutes a minor fraction of total investments for a given year, and probably it will not follow the same replacement patterns as other parts of investments.

The GREEN model of the OECD (Burniaux et. Al., 1992), describes capital vintages with different substitutability between energy and labour. The most recent vintage has the highest degree of substitution.

Vintage models for the capital of electricity and heat production

For electricity and heat production and to some extent other energy intense industries the energy consumption will be more closely related to a capital vintage. The physical lifetime for capital in this sector is long compared to capital in other sectors. Energy efficiency or fuel efficiency will be closely connected to the initial investment in e.g. a new power plant. The fuel efficiency can be improved only by relatively large investments in the period after erection of the plant. It is also possible that later investments in an existing plant will decrease the fuel efficiency instead of improving it. This can be the case if investments are directed at de-sulphuring equipment, which decreases the net output of electricity from a power plant. Technology diffusion is in the case of electricity and heat production the main explanation for changes in energy efficiency. In the short term the change in aggregate efficiency in this sector will also be related to production changes and capacity utilisation rates. In section 5 these issues are examined in a model of electricity and heat production. The capacity utilisation issue can be one of the factors that makes it difficult to find empirical evidence for the importance of embodied technical change in other sectors.

Vintage models of electric appliances

In these models the average electricity consumption of a vintage of different kinds of appliances is in focus. Often these models include different brands of a specific type of appliance with different electricity consumption. It is not explained why different brands with different efficiencies are being bought every year. Instead it is assumed that the spread between the most and the least efficient brand of an appliance is constant in time. In this way there will be policy options for regulating the efficiency for the brands, which are allowed to stay in the market. The diffusion of technologies will be affected by policy. The change in the stock of each type of appliance is often described by assumed penetration functions e.g. based on an estimation of a logistic distribution in households. Some vintage models of electric appliances include links where economic variables affect the speed with which penetration rates approach an assumed saturation level. Another aspect is the intensity of use for each appliance. Some appliances will be used with the same intensity no matter what the economic conditions and the electricity price are. Other appliances will be used more or less depending on electricity prices and income. This last effect is included in some vintage models of appliances and has an influence on the average efficiency if measured as electricity consumption relative to the stock of appliances.

Vintage models of appliances can be based on epidemic models for technology adoption and in this way they are sector specific versions of the macroeconomic models of Meijers (1994).

4. What are the advantages of vintage models for energy supply and demand?

This section focuses on the relations that affect technological development and the explanations that can be analysed by vintage models. Especially the capability of improving an exogenous description of energy efficiency developments in a wider model context is in focus. There are several interesting issues and questions:

- Is the embodiment hypothesis more relevant for capital intensive and long-lived capital sectors as electricity and heat production?
- What about the rate of capacity utilisation? Is this question more important for average efficiency than the vintage effects of the capital investments?
- Are new vintages used more than old ones?
- Do environmental policies affect the development of energy technologies?
- Do energy prices affect the speed of implementation?

More or less reasonable assumptions regarding the development of these already known specific technologies can be used to describe the energy efficiencies of future vintages of capital equipment. A description of the existing capital stock and the efficiencies of different vintages of this capital stock can be used for identifying the efficiency of the capital vintage that is being replaced. The speed of replacement or expansion of production capacity is determined by activity in the sectors of the economy. This is a practical and realisable strategy only for certain areas of capital equipment. This approach can be applied only to sectors where capital is long-lived and the technologies are identifiable.

Vintage effects play an important role in determining the rate of technological improvement in energy efficiency. Some relevant examples are electricity and heat production, household consumption of energy for heating and electric appliances. In the next two sections vintage models for these sectors are used to illustrate some of the important issues identified above.

5. Technological development in a vintage model of electricity and heat production

The aggregated energy efficiency based on a technical energy-economy model illustrates some of the interdependencies between technological development, investments, capacity utilisation and public policy. These dependencies are illustrated by using a Danish model and the Danish energy system as a case. A case from electricity and heat production emphasises the partly endogenised average energy efficiency in electricity production - fuel price and policy influence the average efficiency development.

The model named Hybris[11] on which the examples are based was a result of an integration project covering Danish models based on bottom-up and top-down approaches to energy-economy modelling. The model is described in Jacobsen (1998)[12]. The purpose of that project was to identify theoretical and methodological problems for

[11] Hybrid interactive simulation

[12] A more detailed description can be found in Jacobsen et. al. (1996)

integrating existing models for Denmark and to implement an integration of the models. The model is integrated through a number of links between energy bottom-up modules and a macroeconomic model. Bottom-up modules replace both electricity and heat supply of the macroeconomic model as well as part of the energy demand in the macro model. With this model it is possible to analyse top-down instruments such as taxes in combination with bottom-up instruments such as regulation of technology choices for power plants and energy standards for household electric appliances.

The electricity and heat supply module in Hybris is a vintage model with technical characteristics for each category and vintage of power plants. Long-term technology choices are seen mainly as restricted by public regulation. Short-term production decisions are unregulated. The model include four categories of producers: major combined heat and power plants, secondary combined heat and power plants, wind power and district heating producers. The largest part of production takes place at major power plants. This category is also the part of the vintage model with most detail and the most sophisticated modelling. Fuel input in electricity and heat production by major plants is found by minimising total fuel cost for electricity and heat generation by the major power plants of Denmark, which are primarily combined heat and power plants. Technical input data are shown in the appendix. In minimising production cost substitution between fuels is allowed within the technical constraints specified for each plant. Fuel demand from each plant is found based on a duration curve for electricity demand. This duration curve is based on the assumption of 365 identical 24-hour periods, and the use of a linear approximation. Heat is assumed to be storable to the extent necessary within the 24-hour period and no duration curve is applied here.

Given the cost minimising fuel mix on each plant they are sorted according to marginal costs. Thus substitution between plants with differing production costs takes place within the bounds given by the duration curve. Plants with high marginal costs (fuel costs) will have short producing times, but as long as the peak demand includes the capacity they will produce. This is the reason that the effect of new production capacity on average efficiency (see Figure 3) is greater than if it were based only on the capacity.

As the production frontier of each plant is constrained by linear restrictions the calculations for the centrally planned operation of large power plants in Denmark is characterised as a linear optimisation problem. The dual problem to the minimisation problem of fuel costs is maximising revenues, which is done at the decentral level. For each plant the production is found by maximising the revenue based on shadow prices for heat and power. By running two iteration procedures the required electricity and heat production is distributed on individual plants. First, electricity production is distributed according to the marginal production cost given the shadow price of heat. At the upper iteration level the shadow price of heat is adjusted to reach the required heat production. In this way, the combined production cost of heat and power is minimised for the large power plants.

Fuel use for the production of power and heat is found by

$$E = \sum_{i=1}^{n} \frac{\left(P_i + Q_i\right)}{\eta_i(f_i)} \tag{1}$$

P_i Electricity production at plant i

Q_i Heat production at plant i

f_i Fuel mix at plant i
η_i Fuel efficiency at plant i,
$P_i + Q_i$ is found by specifying full load hours for each plant exogenously[13] or by the production that results from sorting the plants by the marginal production cost of electricity and setting their production according to their position along the duration curve until the plants necessary to meet the total electricity demand are put into operation.

Fuel demand from secondary power and heat units is calculated with an exogenous capacity and exogenous number of full load hours. The expansion technology for the new plants is handled exogenously, but technical parameters change over time and the endogenous expansion of production capacity in large units acquires the technical parameters determined by the year they are built.

Four different elements that contribute to changes in fuel efficiency in the electricity-producing sector are:

- Production changes and the corresponding change in utilisation rates for the existing capital
- Fuel prices
- New vintages of power plants with increasing fuel efficiency
- Policies which regulate the technology of new vintages of production capacity

The first element has mainly short-term effects, while fuel price changes can have both short- and long-term effects through two different channels. The last two elements have mainly long-term effects on fuel efficiency.

The energy supply model is run with the historical observations of energy demand, production capacity and fuel prices for the period 1990-1996. For the following years fuel prices are projected and energy demand is a result of the macroeconomic part of the model. Thus the projected change in electricity production follows the domestic electricity demand development.

Danish power production has fluctuated substantially in recent years. This is illustrated in Figure 1, where 1991 and 1996 experience nearly 50% increases in production. In 1992 and 1995 production fell. Increasing production was accompanied by a decrease in fuel efficiency for the largest production increases. Corresponding to this a decrease in production was accompanied by improvements in energy efficiency. Production changes and capacity utilisation rates thus have an important impact on yearly changes in average efficiency in power production.

[13] There is an option in the model to exogenously specify production for each major plant, but the default is the endogenous production determination for each plant.

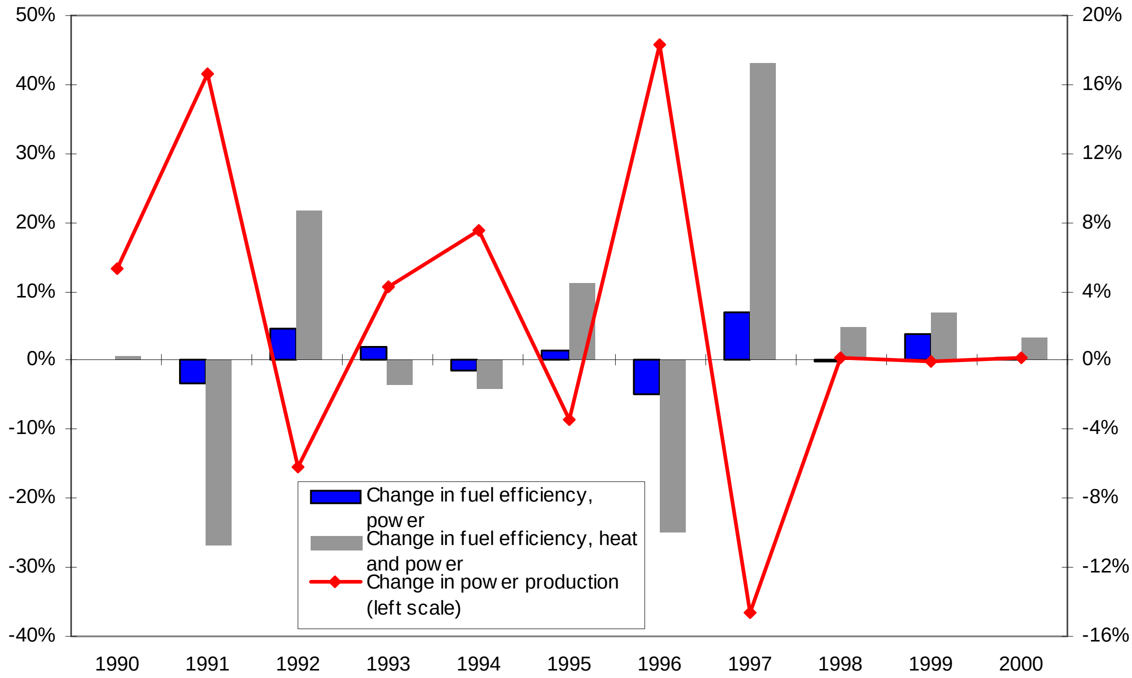

Figure 1 Annual changes in fuel efficiency and in power production

The cost curve for the major power plants in Denmark for 1996 shown in Figure 2 is based on fuel costs alone. Even in an extreme year as 1996 with a very high production due to low water resources in Scandinavia, 90% of total production is delivered from plants situated at the flat part of the cost curve. This means that the decrease of fuel efficiency by around 2% in 1996 is caused by a shift in production share within this group of plants. A group of plants that will in an average year be running less than full capacity measured in hours will in the extreme export year 1996 be running at full load.

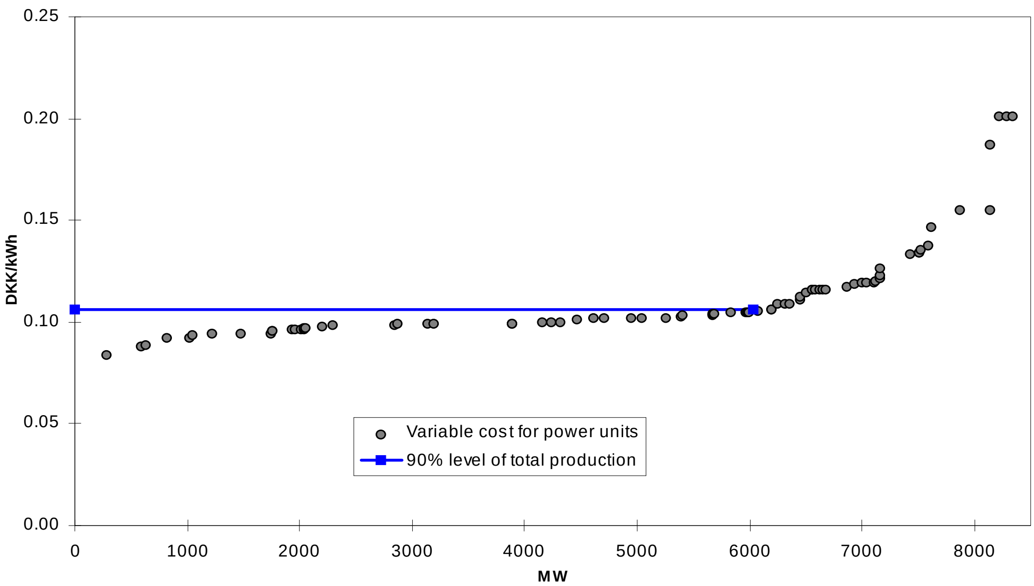

Figure 2 Marginal production costs for major Danish power-producing units 1996

The large share of capacity situated at the flat part of the cost curve secures that production changes have only moderate effects on average fuel efficiency in contrast to what would have been the case if the cost curve had been steeper sloped.

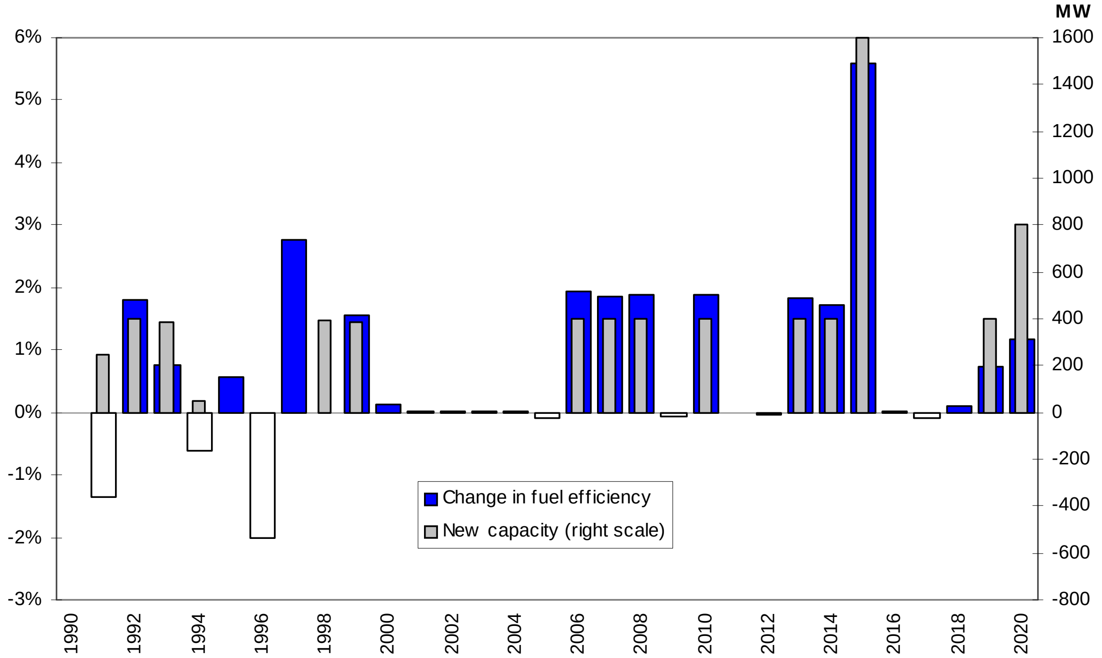

Figure 3 Fuel efficiency changes (year to year) relate to introduction of new capacity

Fuel efficiency changes in the projection period (1997-2020) vary a lot as in the simulation period. The unsteady pattern in the projection period is a result of the introduction of new plants. As a new plant (400 MW) is introduced the average efficiency improves around 2% compared to the previous year. New plants improve the overall efficiency because their fuel efficiency is better than the older plants. High fuel efficiency corresponds to low marginal production cost[14] which enable new plants to capture a relatively large share of the total production. The new plants are running nearly all year and produce around 5% of the total production by major power plants.

The introduction of new plants of course improves efficiency only if the new plant is actually running. In 1998 this is not the case because the new plant in 1998 uses natural gas and the projected prices in this case exclude the new plant from running when production costs are being minimised. The small decreases in efficiency observed in the projection period are a result of reduced production by the major plants. Due to increasing production by renewables the share of production for the major power plants decreases. This again decreases the production share of the new and high-efficiency plants within the group of major power plants.

[14] Given that it is the same fuel that is being used or fuel prices does not differ.

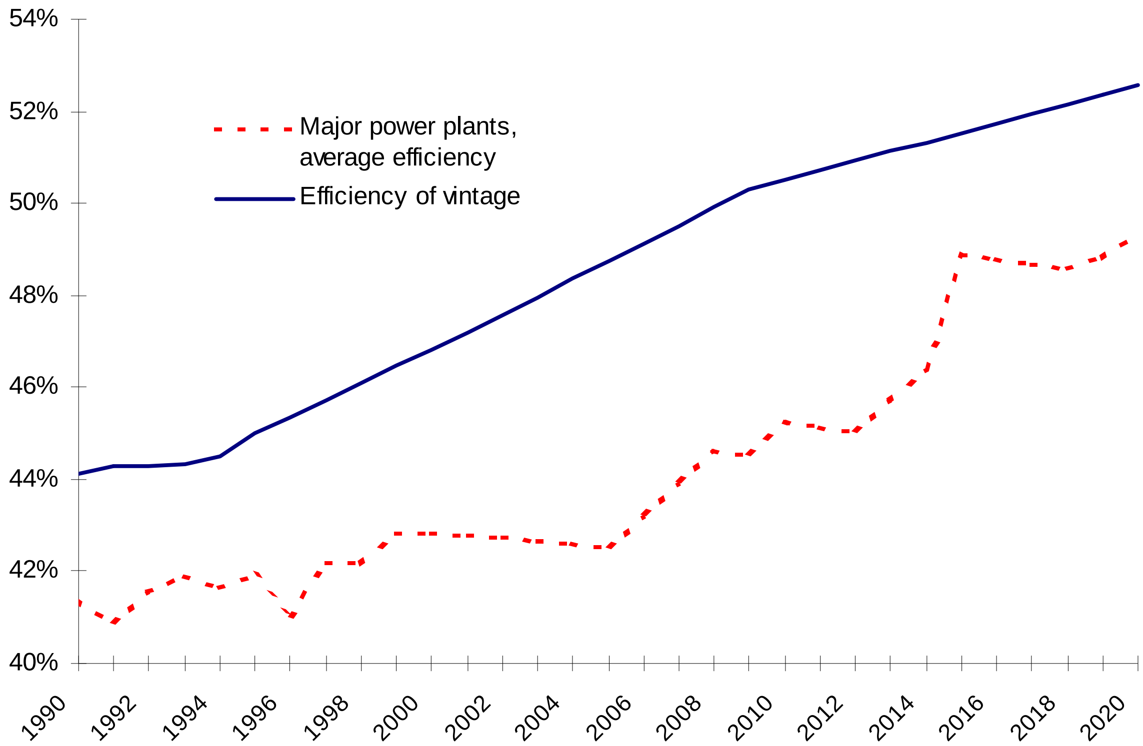

Figure 4 Fuel efficiency in electricity production

The vintage effect in the projection in Figure 4 is evident from the stepwise increase in the average efficiency. Also the periods of no replacement of plants result in increasing the efficiency gap between the best available technology of this vintage and the average technology in use. The gap varies between 3% and 6%, but as long as efficiency increases the average efficiency will always be below the efficiency of the best available technology. This is a consequence of using the vintage model approach. In this case it is irrelevant to try to eliminate the efficiency gap as it is not a result of market imperfections and having all production on the new vintage only would imply enormous costs. Increased speed of diffusion will be associated with higher capital costs.

The issue of public policy become important when it is no longer a narrow definition of fuel efficiency in electricity production that is examined but instead an aggregate measure for the use of fossil fuels to produce the demanded electricity. Such a measure is, for example, the relevant one if it is intended for an input to a top-down macroeconomic model with a very simple representation of the electricity-producing sector[15]. The expansion of wind energy decreases the fossil fuel input in electricity production. This is accomplished by increasing the capital input in electricity production and possibly thereby decreasing the capital productivity. This could have been the case without regulation, but if the wind capacity expansion is a result of public policy this policy has a remarkable and of course intended influence on fossil fuel use for electricity production. This effect would be difficult to quantify in another model that did not have the detail found in this model of electricity and heat production. Thus, for all model-

[15] A fast improvement in "efficiency" in a top-down representation could be justified by such an underlying move towards renewable energy sources.

based analyses of energy policy instruments, for example, a policy to promote renewable energy, a detailed energy technology description will be important.

Efficiency indicators are relatively unproblematic at the disaggregated level of fuel (TJ) used for electricity production (kWh). Compared to this the aggregation of fuels and comparison with GDP developments is a much less accurate measure of energy efficiency. Therefore the concepts of fossil fuel content and the primary energy intensity will be used instead. The importance of the policy to promote wind power expansion is seen in the series for fossil fuel content in Figure 5. The decline in fossil fuel content in electricity production is an important contributor to the reduction in economy-wide primary energy-intensity[16]. Fossil fuel content decrease much faster than the fuel efficiency of major power plants in Figure 4 increase.

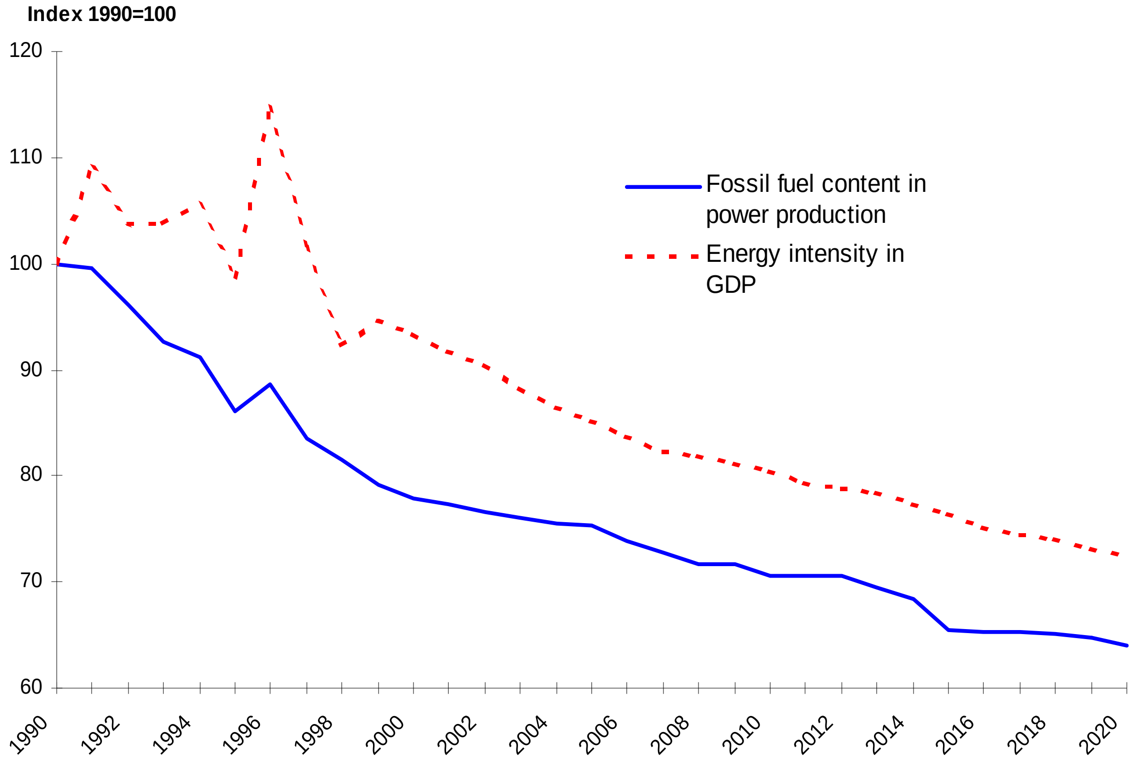

Figure 5 Fossil fuel in electricity production and energy intensity of the Danish economy

In Figure 5 the energy intensity[17] of the economy fluctuates more than the fossil fuel content of electricity production. The changes in electricity production are the reason that the energy intensity of the economy fluctuates considerably. This fact has led the Danish authorities to adjust official figures for primary energy consumption and energy intensity. Official figures from The Danish Energy Agency are adjusted for electricity import and exports as well as for climatic deviations from an average year. But making adjustments could be taken much further to compensate for changes in trade balances, structural changes of domestic production and consumption patterns etc. This could

[16] The thermal energy equivalent of wind is not included in the energy intensity measure. This is reasonable as long as the energy intensity measure is interpreted as an indicator for environmental pressure or pollution from final energy demand. If the energy intensity is interpreted instead as an indicator for the dependence/importance of energy the thermal equivalent should be included.

[17] Energy intensity is defined as primary energy consumption excluding renewable energy sources (TJ/mill. DKK, 1980 prices).

lead to even more detailed decomposition analyses of what is the basic development of efficiency.

Figure 5 shows that in the long run energy intensity declines more gradually than the fossil fuel content of electricity production as opposed to the development in the first years. The importance of the electricity sector for the economy-wide energy intensity is strongest in the first years. In the projection period there are no large fluctuations in electricity production because the variables of climate and trade in electricity are assumed constant. These two assumptions are very natural but also crucial assumptions for the steady decline in the projected energy intensity in Denmark.

6. Energy efficiency changes in residential heating demand and electricity for appliances

This section illustrates technology diffusion in a model of residential heat demand and a vintage model of electric appliances in households.

The model of residential heat demand is used to examine household energy efficiencies and the consequences of energy policies or energy prices. Different heating technologies are described with their local efficiencies. The efficiencies of these technologies are weighted by their share in household heating demand. In Figure 6 the annual change in the average heating efficiency is compared to the annual change in average consumer price for heating in households. Both series are three-year moving averages.

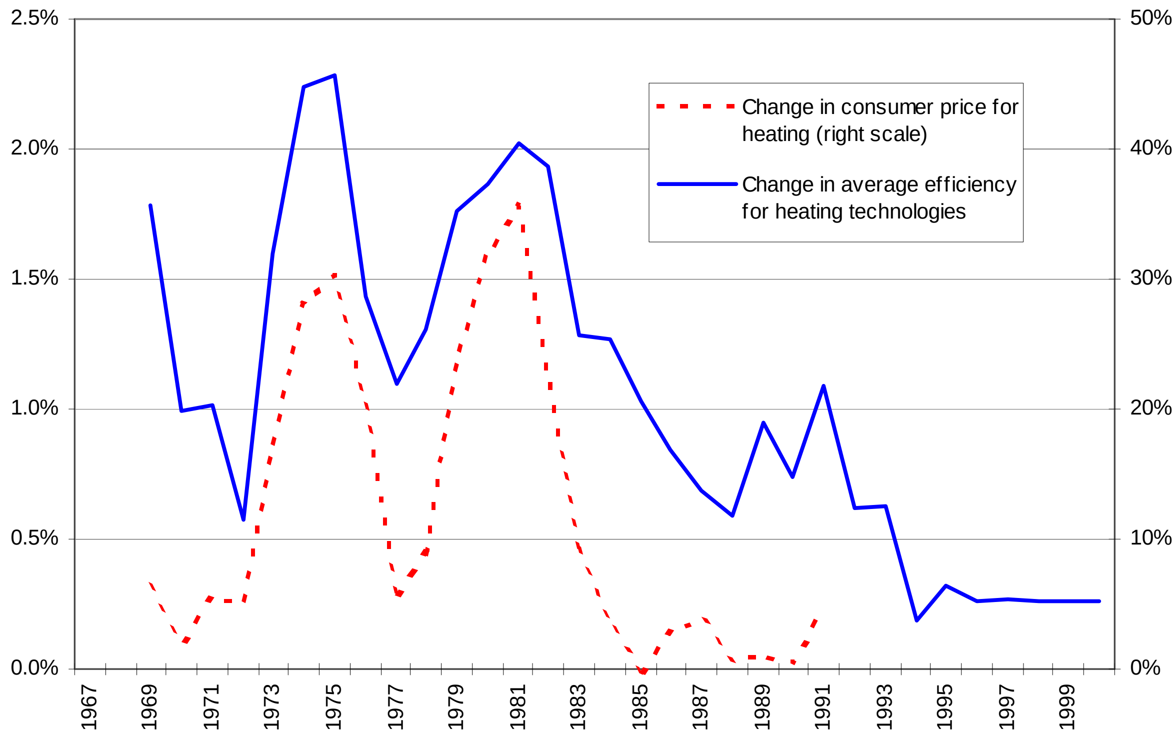

Figure 6 Annual change in average heating efficiency depends on prices

The Figure 6 shows the annual change in efficiency for the heating technologies used for a given year in the residential sector. The annual efficiency change is surprisingly closely related to price changes. This is caused mainly by changes in the composition of technologies and less by changes in efficiencies for the individual technology. It seems as if the implementation of the most efficient technologies is faster during times of sharply rising prices. What is not shown in this simple comparison is the change in energy consumption for each technology. The share of district heating is increased during times of sharp price rises and the local efficiency is much higher for district heating than for liquid fuel-based local technologies. This depends on an increased coverage of district heating, but probably also on a reduction in the use (intensity) of the more fuel-price dependent technologies. Altogether this points to fuel prices as an important parameter for substitution between available technologies and thus for the change in average energy efficiency.

Electric appliances in households are often modelled as vintage models with different electricity consumption for different vintages. Vintage models of appliances often include a lot of detail. This is also the case in the model used here where 15 different types of appliances are included with different lifetime and specifications of average energy consumption for each vintage. Prices for the different versions of a given type of appliance are not included in the model and the consumer choice between the different versions is not explained. Diffusion of the relatively more energy efficient technology does not depend on prices. Therefore the model is incapable of addressing the cost of regulation.

Energy demand for a given year is basically found by adding over the different appliances and the vintage characteristics

$$E = \sum_{s=1}^{n} \eta_s \sum_{i=t_0}^{t} B_{i,s} \; e_{i,s} \qquad (2)$$

$B_{i,s}$ Stock of appliance s, vintage i

$e_{i,s}$ Electricity consumption by each unit of appliance s, vintage i per unit of use

η_s Intensity of use for appliance s

The stock of appliance s of vintage i at time t is given by

$$B_{i,s} = S_{i,s}(1-a_{i,s})^{(t-i)} \qquad (3)$$

where $1/a_{i,s}$ is average lifetime for the vintage of appliance s; and $S_{i,s}$ is the size (sales) of vintage i of appliance s.

The vintage model is combined with an epidemic model of technology diffusion. The development in the stock of appliances is assumed to be determined by penetration ratios for households (share of households, which have a specific appliance). Penetration ratios are specified as following logistic functions, and for some of the most important appliances parameters of these functions are estimated. The logistic function implies that saturation levels exist. For example, it is natural to assume that a household would never have more than one washing machine. In epidemic models the usual assumptions about the development of penetration ratios exclude income and price effects on the stock of appliances. In the model applied here this is modified by letting annual sales for a number of the most electricity intensive appliances depend on the development in consumption of durable consumer goods as determined in the macroeconomic part of the Hybris model. If the resulting annual sales increase the penetration ratios too fast the economically linked sales figures are adjusted downwards to avoid exceeding the saturation levels. This effect will in the longer run tend to decrease the sales figures and hereby electricity demand as penetration ratios are approaching the exogenously given saturation levels.

There are several arguments against the aggregate determination of residential electricity demand by models such as those applied here[18], but for the individual appliance this kind of model has valuable information on technological diffusion. One of the 15 appliances, the dishwasher, has been included to illustrate technological diffusion in a vintage model of appliances.

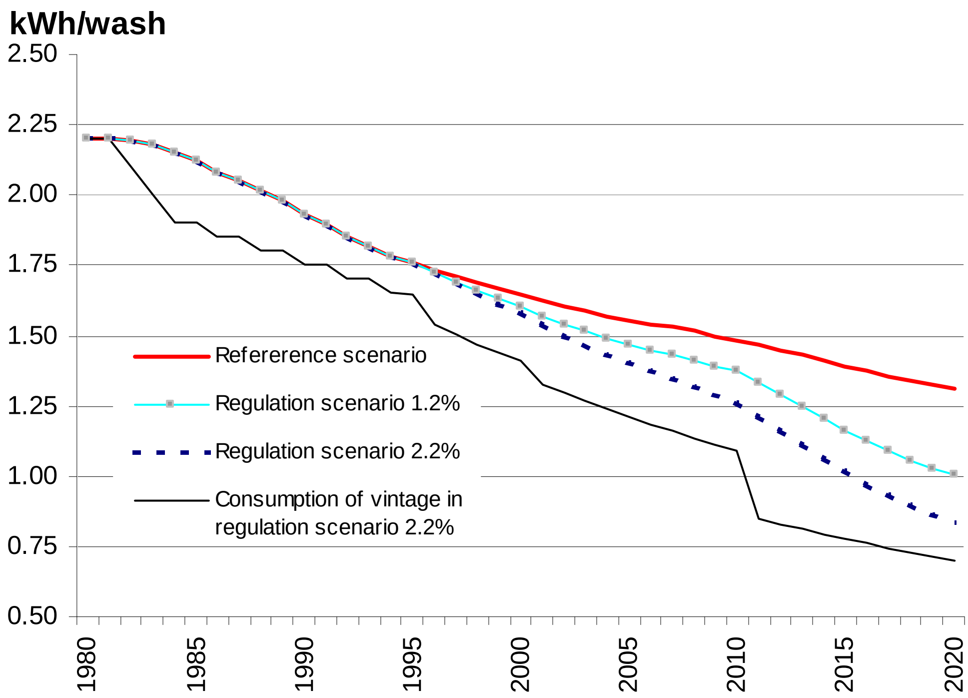

Figure 7 Average electricity consumption of dishwashers

In this example technological diffusion is dependent on regulation of the technology options for the consumer. The speed of diffusion for **energy**-efficient technologies is increased by introducing standards. A gradual tightening of the standards for electricity consumption of dishwashers in the years 1996, 2001 and 2011 enforces the regulation. From 2011 only the most efficient model that was found in the market in 1994 is allowed. Regulation scenarios are shown with assumptions of 1.2% and 2.2% annual improvements in energy efficiency for all of the models available. The energy consumption of the average dishwasher is 40% lower in 2020 for the regulated scenario (2.2%) compared to the reference. Part of this difference can be attributed to the assumption of annual improvement in efficiency for all of the different brands and models of dishwashers. It is somewhat arbitrarily assumed that due to the regulations the yearly improvement in efficiency for the individual models increases from 1.2% to 2.2%. The argument is that the producers will seek to improve their technology in order to stay in the market. The producers will be forced to pay more attention to the electricity consumption in the development of new models of dishwashers. A main

[18] One argument is the lack of a price effect from the price of a given appliance to the volume of sales. Another weakness is the lack of innovation. No description and explanation of the emergence of new appliances that in the long run can have a considerable effect on residential electricity demand.

argument against this reasoning is that in the case of Denmark the importance of the Danish market will be marginal for the development policy of producers. In the case of international standards the relevance of an increased rate of improvement in technology would be higher.

In this example the issue of costs is not addressed, but there will be costs to the consumers in the way that the number of options for choosing a dishwasher has been decreased. The more energy efficient dishwasher will very likely be more costly but it is not possible to tell if the lower energy consumption, a longer lifetime or a more sophisticated appliance will balance the initial higher costs.

Technology diffusion depends on expansion of the stock of dishwashers and the replacement rate of dishwashers. In the regulation scenario (2.2%) for 2010 the difference between the average dishwasher in the stock and the average efficiency of 2010 vintage is of the same size as the improvement in the stock of dishwashers relative to the reference scenario.

In the long run the relevance of these vintage models of electric appliances will be limited. The aggregated projection of residential electricity consumption by such models will be influenced by the lack of projection for new kinds of electric appliances. Even for a specific appliance as a dishwasher the washing technology could be replaced by a new technology in a horizon of 15-25 years.

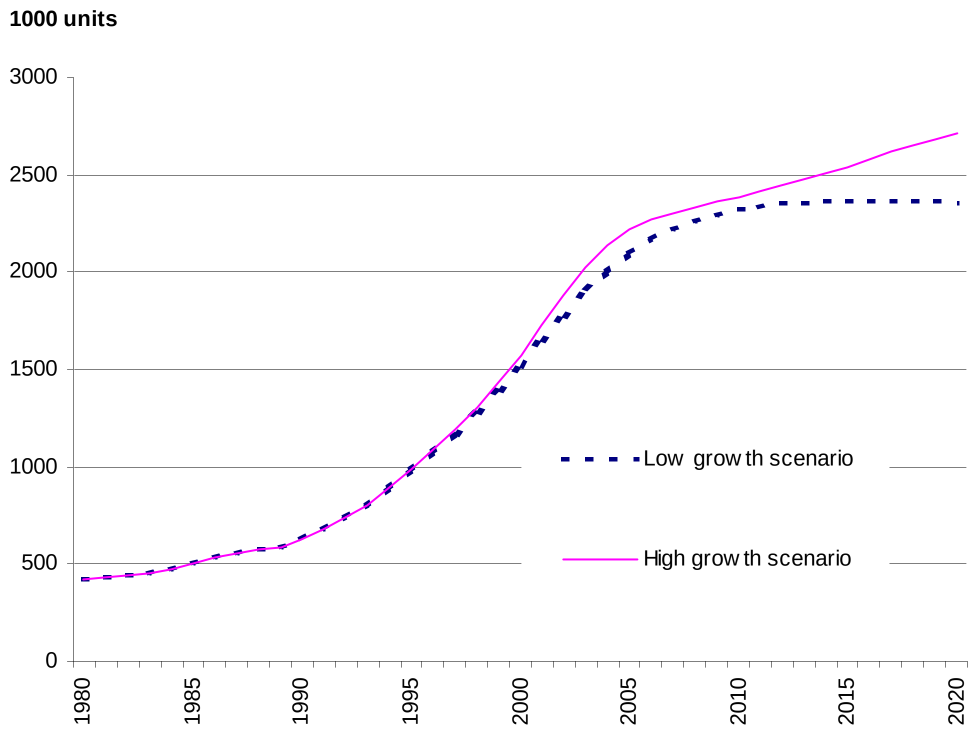

Figure 8 The stock of dishwashers and the dependence on economic growth

The diffusion of energy technologies and the dependence on economic growth can also be examined in a vintage model of electric appliances. In the vintage model where the example of dishwashers is taken from private consumption of durable goods affects the rate of expansion in the stock of important groups of appliances. This is also the case for dishwashers. The dependence on economic growth for technology diffusion measured as average energy efficiency for the stock of dishwashers is illustrated in an example with a much slower growth than in the previous example. The effect on the stock of dishwashers is not large but the stock is 15% lower compared to a decline in consumption of durable goods of 40%. Suggesting that in this appliance model the implicit income elasticity of dishwashers is much lower than the average income elasticity of durable goods. This is because it is only the rate of increasing the penetration ratio for dishwashers and not the saturation level of household penetration of dishwashers that is affected.

The long-term change in the stock of dishwashers has absolutely no impact on the average energy efficiency of dishwashers in 2020. This can be attributed to the relatively shorter lifetime of electric appliances compared to the power plants in the previous example. Also the development of installed appliances is much more gradual even though the level of sales has been decreased due to slower growth. Another reason is that the efficiency improvement of vintages comes gradually and not in a discrete manner as in the case of introducing new technologies or in the case of tightening standards at some point in time. Thus, this vintage model has no vintage effect on average efficiency from changes in sales that are a consequence of changed economic growth.

7. Conclusions

Technological progress is a critical parameter for analyses of energy and environmental issues. In the long-term technological progress will be dominated by innovation but in a short- to medium-term perspective the diffusion of technologies can be more important.

Macroeconomic energy-economy models have an aggregated and generalised description of the change in energy technologies. Some of these models include innovation by endogenising technological change at the aggregated level, but it is very difficult to empirically verify the endogenisation. Bottom-up vintage models exclude the innovation aspect. Instead they focus on the description of a large number of specific technologies and their expected improvement. In the short- to medium-term perspective these kinds of models will provide a better description of technology diffusion provided that they are linked to economic variables affecting investment decisions.

With technical bottom-up based models the vintage effect of a new capital vintage on average efficiency can be quantified. It is possible to include effects related to the division of production between different vintages of capital as exemplified by the vintage model of electricity and heat production. In this model new capital will be used to a relatively greater extent than older capital, but when capital utilisation rates increase the use of older less efficient capital increase relatively more than new capital. The change in utilisation rates affects the average fuel efficiency for electricity and heat by op to 20%.

Energy and environmental policies have an important impact on fuel efficiency. It is difficult to quantify the effect of specific technology-oriented policies if an aggregated energy-economy model is being used. Policies of this kind could be evaluated using the vintage model of electricity and heat production, which give a consistent quantification of policies including those effects, which work through prices and demand. The Danish energy policy to increase the use of renewable energy, especially wind-energy, of course increases the total fuel efficiency for electricity production. This effect that considerably reduces the use of fossil fuels in Denmark can be quantified with the vintage model.

Electric appliances are often modelled in vintage models. Such a description could be based on either estimated logistic functions of technology penetration or just related to some saturation levels. In the model applied in this study a link to economic activity has only a minor impact on the average efficiency of the stock of dishwashers even though the impact on the stock itself is of some size. This illustrates the different characteristics of capital in electricity and heat production compared to the electric appliances. The discrete nature of investment in power plants is very important for average fuel efficiency but the much more gradual replacement of electric appliances result in less impact on average efficiency. For the producing sectors where the replacement of energy using equipment also follow a more gradual pattern, at least for a sector on average, the technology diffusion will result in a more gradual energy efficiency improvement.

Fuel prices in the case of residential heating technologies also seem to have an impact on the rate of replacement and on the average efficiency of the heating technology. This is a result of the large fuel share in the total cost of residential heating.

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Appendix: Technological parameters for major power plants

Name	Num-ber	Power capacity	Heat capacity	Fuel effici-ency power	Availa bility	Plant type	Cm	Cv	Start	Scrap	Coal max	Coal min	Oil max	Oil min	Natu-ral gas max	Natu ral gas min	Bio-mass max	Bio-mass min
		MW	MJ/s						year	year	%	%	%	%	%	%	%	%
FVO 93	1	47	0	0.37	0.83	1	0.50	0.14	1993	2003	100	0	100	2	0	0	0	0
FVO B2	2	195	233	0.37	0.83	2	0.56	0.13	1968	1995	100	0	100	4	0	0	0	0
FVO B3	3	269	279	0.40	0.83	2	0.68	0.17	1974	2003	100	0	100	6	0	0	0	0
FVO B7	4	400	450	0.44	0.83	2	0.68	0.15	1991	2020	100	0	100	5	0	0	0	0
MKA T9	5	90	93	0.34	0.83	2	0.43	0.14	1960	1994	100	60	40	1	0	0	0	0
MKA T10	6	70	93	0.34	0.83	2	0.43	0.14	1965	1995	100	60	40	1	0	0	0	0
MKS B1	7	152	0	0.42	0.83	1	0.43	0.14	1968	2007	100	0	100	2	0	0	0	0
MKS B2	8	262	0	0.41	0.83	1	0.43	0.14	1972	2002	0	0	100	100	0	0	0	0
MKS B3	9	350	455	0.42	0.83	2	0.57	0.18	1984	2013	100	0	100	2	0	0	0	0
MKS B4	10	350	455	0.42	0.83	2	0.57	0.18	1985	2014	100	0	100	2	0	0	0	0
RKE B1	11	52	105	0.86	0.83	3	0.43	0.00	1983	2012	100	100	0	0	0	0	0	0
NEV B1	12	130	15	0.37	0.83	2	10.00	0.29	1967	1996	100	0	100	3	0	0	0	0
NEV B2	13	295	42	0.40	0.83	2	3.50	0.13	1977	2006	100	0	100	2	0	0	0	0
NK T5	14	41	70	0.33	0.83	2	0.43	0.15	1958	1998	100	40	60	2	0	0	0	0
NK T6	15	74	133	0.33	0.83	2	0.43	0.13	1962	1998	100	40	60	2	0	0	0	0
NK B1	16	269	291	0.41	0.83	2	0.60	0.15	1973	2002	100	0	100	2	0	0	0	0
NE/NK 9	17	385	400	0.47	0.83	2	0.80	0.12	1998	2027	100	0	100	5	0	0	15	0
SVS B1	18	100	134	0.38	0.83	2	0.60	0.15	1964	2003	100	0	100	2	0	0	0	0
SVS B2	19	269	118	0.41	0.83	2	0.60	0.19	1971	2000	100	0	100	2	0	0	0	0
SVS B3	20	394	450	0.49	0.83	2	0.60	0.15	1997	2026	0	0	0	0	100	0	0	0
SHE EV2	21	144	21	0.38	0.83	2	0.43	0.16	1965	2000	100	30	70	1	0	0	0	0
SHE EV3	22	600	78	0.41	0.83	2	0.41	0.17	1979	2008	100	0	100	2	0	0	0	0
ØKR	23	67	0	0.37	0.83	1	0.50	0.00	1965	2000	25	0	100	2	0	0	0	0
VKE B1	24	125	169	0.37	0.83	2	0.50	0.16	1965	1995	100	9	91	1	0	0	0	0
VKE B2	25	245	290	0.41	0.83	2	0.60	0.16	1969	1998	100	0	100	1	0	0	0	0
VKE B3	26	388	400	0.46	0.83	2	0.70	0.16	1992	2021	100	0	100	1	0	0	0	0
HERN. B1	27	89	174	0.92	0.83	3	0.51	0.00	1983	2012	100	0	100	5	0	0	0	0
AMV 1	28	136	150	0.39	0.83	2	0.68	0.15	1971	2006	100		100	2.5	0	0	0	0
AMV 2	29	128	145	0.39	0.83	2	0.68	0.15	1972	2007	100	0	100	2.5	0	0	0	0
AMV 3	30	250	330	0.42	0.83	2	0.58	0.15	1989	2019	100	0	100	2.5	0	0	0	0
ASV 1	31	140	0	0.39	0.83	1	0.60	0.00	1959	2001	100	0	100	2.5	0	0	0	0
ASV 2	32	145	0	0.39	0.83	1	0.60	0.00	1961	2005	100	0	100	2.5	0	0	0	0
ASV 3	33	270	116	0.40	0.83	2	0.41	0.15	1967	2001	100	0	100	2.5	0	0	0	0
ASV 4	34	270	58	0.40	0.83	2	0.41	0.15	1968	2004	100	0	100	2.5	0	0	0	0
ASV 5	35	695	0	0.41	0.83	1	0.60	0.00	1981	2015	100	0	100	2.5	0	0	0	0
AVV	36	250	330	0.42	0.83	2	0.60	0.15	1990	2020	100	0	100	2.5	0	0	0	0
HCV 1+4	37	79	581	0.85	0.83	3	0.40	0.00	1962	1997	80	25	75	20	0	0	0	0
HCV 5	38	70	0	0.34	0.83	1	0.60	0.00	1965	1998	100	100	0	0	0	0	0	0
HCV 7	39	88	182	0.85	0.83	3	0.48	0.00	1985	2015	100	0	100	2.5	100	0	0	0
HCV 9	40	12	0	0.29	0.83	1	0.60	0.00	1934	2000	0	0	100	100	0	0	0	0
KYV 11-13	41	195	0	0.35	0.83	1	0.60	0.00	1953	2000	100	0	100	2.5	0	0	0	0
KYV 21	42	260	0	0.35	0.83	1	0.60	0.00	1974	2015	0	0	100	100	0	0	0	0
KYV 22	43	260	0	0.35	0.83	1	0.60	0.00	1976	2015	0	0	100	100	100	0	0	0
KYV 41	44	20	0	0.37	0.83	1	0.60	0.00	1973	2015	0	0	100	100	0	0	0	0
KYV 51	45	65	0	0.27	0.83	1	0.60	0.00	1973	2015	0	0	100	100	0	0	0	0
KYV 52	46	65	0	0.27	0.83	1	0.60	0.00	1973	2015	0	0	100	100	0	0	0	0
MAV 11	47	75	0	0.37	0.83	1	0.52	0.00	1960	1994	100	0	100	2.5	0	0	0	0
MAV31	48	70	0	0.27	0.83	1	0.60	0.00	1975	2015	0	0	100	100	0	0	0	0
SMV 1+3	49	71	370	0.85	0.83	3	0.19	0.00	1955	1997	0	0	0	0	100	100	0	0
SMV 5	50	35	0	0.29	0.83	1	0.60	0.00	1958	1992	0	0	0	0	100	100	0	0
STV 1	51	143	0	0.40	0.83	1	0.60	0.00	1966	2001	100	0	100	2.5	0	0	0	0
STV 2	52	270	0	0.41	0.83	1	0.60	0.00	1970	2005	100	0	100	2.5	0	0	0	0
NEW 1	53	400	392	0.49	0.83	2	0.87	0.15	2005		100	0	100	2.5	0	0	50	0
NEW 2	54	400	384	0.49	0.83	2	0.89	0.15	2006		100	0	100	2.5	0	0	50	0
NEW 3	55	400	376	0.50	0.83	2	0.91	0.15	2007		100	0	100	2.5	0	0	50	0
NEW 4	56	400	360	0.50	0.83	2	0.96	0.15	2009		100	0	100	2.5	0	0	50	0
NEW 5	57	400	338	0.51	0.83	2	1.03	0.15	2012		100	0	100	2.5	0	0	50	0
NEW 6	58	400	330	0.51	0.83	2	1.06	0.15	2013		100	0	100	2.5	0	0	50	0
NEW 7	59	400	323	0.51	0.83	2	1.09	0.15	2014		100	0	100	2.5	0	0	50	0
NEW 8	60	400	323	0.51	0.83	2	1.09	0.15	2014		100	0	100	2.5	0	0	50	0
NEW 9	61	400	323	0.51	0.83	2	1.09	0.15	2014		100	0	100	2.5	0	0	50	0
NEW 10	62	400	323	0.51	0.83	2	1.09	0.15	2014		100	0	100	2.5	0	0	50	0
NEW 11	63	400	296	0.52	0.83	2	1.20	0.15	2018		100	0	100	2.5	0	0	50	0
NEW 12	64	400	290	0.52	0.83	2	1.23	0.15	2019		100	0	100	2.5	0	0	50	0
NEW 13	65	400	290	0.52	0.83	2	1.23	0.15	2019		100	0	100	2.5	0	0	50	0
NEW 14	66	400	284	0.53	0.83	2	1.26	0.15	2020		100	0	100	2.5	0	0	50	0

Plant type: 1: Condensing 2: Combined heat and power (extraction condensing - variable output mix) 3: Combined heat and power (back pressure – fixed output mix) Cm: electricity heat ratio (electricity output/heat output) Cv: electricity loss ratio (reduced electric output per increase in heat)

Integrating the bottom-up and top-down approach to energy-economy modelling. The case of Denmark*

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department

Abstract
This paper presents results from an integration project covering Danish models based on bottom-up and top-down approaches to energy-economy modelling. The purpose of the project was to identify theoretical and methodological problems for integrating existing models for Denmark and to implement an integration of the models. The integration was established through a number of links between energy bottom-up modules and a macroeconomic model. Bottom-up modules replace the energy supply sector of the macroeconomic model and part of the energy demand in the macro model. Analyses of different aspects of energy demand and environmental implications can be carried out with the model. In this model it is possible to analyse both top-down instruments as taxes along with bottom-up instruments as regulation of technology choices for power plants and energy standards for household electric appliances. The combined initiatives to reduce CO_2 emissions are analysed taking into consideration the interactions between regulation of the energy supply sector, prices and energy demand. It is shown that combining the two kinds of initiatives reduces the emission-reducing effect of each of the instruments remarkably.

JEL classification: Q43, C60

Keywords: Energy-economy modelling; Integration; Bottom-up; Top-down; Denmark; Emission-reducing effect

1. Introduction

Two different approaches to energy-economy modelling exist: top-down modelling based on macroeconomic modelling principles and techniques, and bottom-up modelling based on disaggregation and the inclusion of a large number of technical parameters. The different approaches have led to very different properties and model results which in recent years have been most widely noticed in the analyses of emissions and mitigation costs. Both older (Hoffman and Jorgenson, 1977) and more recent studies

* ***Energy Economics*** 20 (4), p. 443-461.

(Barker et. al., 1995) have argued the need to integrate the approaches, as they are in many cases of a more complementary than substituting nature. Others have argued that the two approaches are incompatible. This is based on that the models are developed with different purposes and designed to permit the performing of different analyses for examining different questions. According to these differences they could not be expected to yield the same results.

Studies exist that integrate or link bottom-up and top-down approaches. These studies range from integrated models with so-called "hard linking", defined as interactions in an iterative procedure, to models that calculate the energy consequences of different economic developments. Models vary between those that are global, regional and even very local. A common purpose for developing these recent examples of integrated models has been the need for analysing environmental issues related to greenhouse gas emissions.

In this study models representing the two approaches were integrated. The purpose of the study was to integrate a bottom-up simulation model with a Keynesian type macroeconometric model and to identify theoretical and methodological problems connected to the integration. Elements of the bottom-up simulation model BRUS[1] (Morthorst, 1993) were developed into new modules which fit the structure of a macroeconometric model. The Danish macroeconometric model ADAM[2] (Danmarks Statistik, 1996), which is the most commonly used macroeconomic model for economic analysis and forecasting in Denmark, was linked to the developed bottom-up energy modules. This combined model was called Hybris (Jacobsen et. al., 1996).

There are important interactions between the energy system and the economy, which makes the integration of bottom-up and top-down approaches an important issue. Integration of the two approaches is also important to ensure that it is the same cost concept which is being used when evaluating bottom-up and top-down options for reducing emissions. The integrated model Hybris is capable of analysing traditional bottom-up and traditional top-down options for reducing CO_2 emissions in the same model. This makes it possible to analyse the dependence of different options or initiatives on each other. The effect of price incentives as fuel taxes depend on the technological options for substituting between fuels and the effect of standards for electric appliances depends on the sales of durable consumer goods. The dependence was quantified with Hybris by running scenarios for bottom-up and top-down initiatives separately and comparing them to scenarios with combinations of reduction initiatives. The effect of 3 different options for emission reduction was found to be highly dependent on each other.

This paper is divided into three parts: The first describes the different approaches to energy-economy modelling, the integration problems and relevant options for integrating. In the next part, the Danish model Hybris and the actual integration followed in this model exercise is described. In the third part of the paper, model

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1 Brundtland Scenario model

2 Annual Danish Aggregated Model

scenarios and calculations are presented to illustrate the properties of the model and the interaction between bottom-up and top-down oriented CO_2 reduction options.

2. Bottom-up and top-down modelling of energy-economy issues

Energy modelling has been undertaken by many different institutions and professions but the models in existence are dominated by two different approaches. Top-down modelling is based on macroeconomic modelling principles and techniques and is intended to include all important economic interactions of the society. Bottom-up modelling is based on disaggregation and technical parameters. The two modelling approaches have been designed with different purposes and with a different theoretical background. This is the main reason for the very different properties and results from using the models for analysing the same issues.

Bottom-up models have been widely used within energy analysis and planning. Models of this type have a lot of detail and describe a number of specific energy technologies with both technical and economic parameters. Both present and future technologies are often included, which means that these models include a description of the change in parameters as, for example, fuel substitution options based on knowledge of the stage of development of new technologies. Bottom-up models in this indirectly way describe changes in parameters which in top-down models would be fuel substitution elasticities. Models based on the bottom-up approach can be either optimisation or simulation models.

Many bottom-up models include energy demand divided into end use demands, for example: heating, lighting, ventilation, process, rather than divided into energy types. This reflects the view that developments in energy demand tend to depend more on the different purposes for which energy is made use of than on the specific energy type and the characteristics related to this type including the energy price.

Bottom-up models of household energy demand are typically based on vintage models of a large number of end use technologies. Penetration rates for each technology, for example, electric appliances, are described as following a time profile with saturation levels. Sometimes penetration rates are just projected exogenously. Energy demand relations for bottom-up models of electricity demand in households could, for example, be specified as

$$E = \sum_{s=1}^{n} \eta_s \sum_{i=t_0}^{t} B_{i,s} \; e_{i,s} \qquad (1)$$

$B_{i,s}$ Stock of appliance s, vintage i

$e_{i,s}$ Electricity consumption by each unit of appliance s, vintage i per unit of use

η_s Intensity of use for appliance s

The stock of appliance s of vintage i at a given time t is given by

$$B_{i,s} = S_{i,s}(1 - a_{i,s})^{(t-i)} \quad (2)$$

where $1/a_{i,s}$ is average lifetime for the vintage of appliance s; and $S_{i,s}$ is the size (sales) of vintage i of appliance s. The development in the stock of appliances is assumed to be determined by penetration ratios for households (share of households which have a specific appliance). Penetration ratios could be specified to follow logistic functions, and in some cases parameters of these functions are estimated for each type of appliance. The logistic function implies that saturation levels exist. For example, it is natural to assume that a household would never have more than one washing machine. Normally assumptions about the development of penetration ratios exclude income and price effects on the stock of appliances. This may be modified by letting sales depend on income or prices. However, saturation levels would often be exogenous. Such modifications will be characterised as incorporating top-down elements into bottom-up models.

Top-down models are characterised by behavioural relations at an aggregated level with parameters estimated based on historical relationships. Both models are used that are developed specifically for analysing energy issues and models of a more general macroeconomic type. The models used for energy-economy modelling are based on different economic traditions and theories, both models with neo-classical and Keynesian origin exist. Also, there is a difference in the time spans covered by the models. The type of macroeconomic model used has a significant influence on the properties of the model including the results of analysing energy issues as, for example, the costs of greenhouse gas mitigation. Top-down specifications of energy demand in households could, for example, be

$$E_j = e(p_i, p_j, aeei, C) \quad (3)$$

p_j Price of different energy types, electricity, district heating, natural gas etc.
p_i Price of other consumer goods or services
aeei Autonomous energy efficiency improvement (indexed)
C Total private consumption

The different approaches reflected in the specifications of energy demand above are a consequence of different theoretical backgrounds and modelling practices. Bottom-up and top-down approaches are complementary in some respects. The autonomous energy efficiency improvement *aeei* is exogenous to the top-down model. When forecasting, the energy efficiency is projected to rise by an exogenous rate each year, which in different model studies range from a yearly efficiency improvement of ½% to 1½%. In the bottom-up model the vintage effect through technology improvement for each new vintage of appliances could give a better description of energy efficiency developments. The longer the horizon the more inaccurate will be the estimate from the bottom-up model.

With regard to the effect of energy price changes, the two approaches are fundamentally different. The macroeconometric approach is based on estimation of historical relations between energy prices and energy demand and assumes that the behaviour reflected in the estimated elasticities is constant. The elasticities imply that to some extent electricity could be substituted by other energy forms and that an energy service to some extent could be substituted by other consumer goods or services. On the other hand, many bottom-up models of household energy demand do not include any response to fuel price changes at all. In bottom-up models it is, for example, assumed that other types of energy cannot substitute electricity. For household heat demand it is assumed that consumers do not respond to higher energy prices by saving energy for heating. Savings depend instead on the public programmes for improving housing standards and the insulation standards for new dwellings.

For disaggregated studies of household energy demand, the macroeconometric approach leads to practical problems that arise in estimating fuel price elasticities. The estimation requires that time series of some length for energy prices and demands are available. These empirical data are not always at hand. For example, in the Danish case when natural gas was introduced for use in households, empirical data for estimating elasticities between natural gas and other types of energy were not present. Due to this lack of data the share of natural gas out of household energy demand will have to be put as an exogenous variable in the macroeconometric model. Further, household energy demand is often regulated and dependent on public policies especially for natural gas and district heating. For example, the penetration of natural gas in households depends on public long-term decisions about expanding networks and making compulsory connections. The bottom-up model could be complementary in this case and used for describing the development of natural gas penetration.

There is a fundamental difference in the way household energy demand responds to income developments. Bottom-up models in general have no response to income developments; for example, they consider housing area to be an exogenous explanation for heat service demand. For electricity, the penetration ratio for each appliance is assumed to follow a logistic function in time and thus there is no connection from income to the stock of each appliance. Top-down models include income effects measured by the total consumption C in (3) and often the long-term effect from income increases is to increase energy demand proportionally.

Bottom-up models calculate the costs of operating the energy system including discounting with a social discount rate. Changes of operating costs caused by alternations in the configuration of the energy system, for example, with the purpose of reducing emissions, are included but the effects on the economy are not included. In contrast to this the top-down model would calculate the cost of emission reduction from the long-term loss in GDP or a change in welfare. This includes the indirect effects on the economy from alternations in the configuration of the energy system. The measures in the bottom-up and top-down approaches are based on different cost concepts, but they are often compared and this explains some of the controversies over cost of greenhouse gas mitigation.

The different approach includes other issues as whether knowledge of economical energy-saving options in industry can exist without implementation taking place (the so-called "no regret options"). The difference often includes both divergent assumptions about behaviour in response to price changes and different assumptions about efficiency developments.

The differences described above have led to very different results for costs of reducing emissions. In IPCC (1996) the difference between the approaches and the consequences for costs has been treated in depth. As argued by Hourcade and Robinson (1996), both top-down and bottom-up models can be optimistic or pessimistic on costs. Bottom-up models tend to be optimistic on the technical cost, while top-down models are often more negative on this issue. Top-down models can be either optimistic or pessimistic regarding the existence of double dividends. The effect of double dividend in a top-down model could produce costs that are negative and in this way the top-down model could be more optimistic than some bottom-up models. The relative advantages of the two approaches for analyses in different fields could be summarised as:

Bottom-up

- Regulation and detailed energy planning
- Restructuring of energy supply sector
- Using standards for housing insulation or electric appliances
- Project the technological development in order to quantify the aggregated development in energy efficiency

Top-down

- Energy taxes
- Effect of different economic scenarios on energy and environment
- Macroeconomic consequences of changes in the energy system
- General equilibrium effects

3. Integration principles

Integration implies choosing from a number of alternative integration principles, which have both practical and theoretical implications for the properties of the integrated model. The options for integration can be grouped as:

- top-down
- bottom-up
- mixed integration principle

A top-down-based principle implies that energy demand is determined by relative prices, income or production and an exogenous energy efficiency. This energy efficiency is quantified from bottom-up calculations that are aggregated to the level of the macroeconomic model. This aggregate describes only the autonomous energy efficiency development. In this way the bottom-up principle applies only to quantifying an exogenous component in the macroeconomic relation. On integrating according to this principle no conflict appears with the top-down modelling approach. On the other hand, the controversy between bottom-up and top-down approaches over macroeconomic effects or costs of reducing greenhouse gases is not dealt with. Integration based on top-down principles with an exogenous energy efficiency ensures that the same basic assumptions regarding technological improvement are used in both model approaches. If the bottom-up energy efficiency is considered to be not only autonomous but a function of investments in production capacity or energy-saving equipment, problems of consistency will arise. How should investments from the bottom-up part be linked to the top-down specification of factor-inputs? The technological improvements in energy efficiency in bottom-up models could, for example, initiate from a higher capital intensity and this could not be transferred to the macro model setup through exogenous efficiency parameters because it involves a re-specification of important relations in the macroeconomic model.

Bottom-up principles[3] used for integration mean that the macroeconomic specification of energy demand is replaced. The importance and possibility of doing this depend very much on the macroeconomic specification used. Replacing energy demand relations is likely to influence relations for total factor demand in producing sectors. Thus, in most macroeconomic specifications the relations for all factor-demand components must be revised and re-estimated. Apart from the practical problems connected to this re-specification and re-estimation, the link to the theoretical basis for the factor-demand specification might be weakened. Figure 1 illustrates the aggregation problems for integrating according to bottom-up principles. The nested levels of determination in macroeconomic top-down models, where for example the factor inputs of energy, capital and labour are determined dependent on each other at an upper level, could imply problems for integrating a bottom-up determined energy input directly. According to a top-down principle the input of different types of energy is found by splitting the total energy input in a relation at a lower level.

Different aggregation levels of the basic relation that determines energy demand in the two approaches lead to problems in integrating the bottom-up modules of energy in the macroeconomic model. Bottom-up determined energy demand is seen as independent of other factor inputs and there is no simple way of adjusting these other factor inputs if the bottom-up relation yields a result other than the top-down relation. Bottom-up models could implicitly include a different substitution between electricity against capital and fuels for process against capital and this would be inconsistent with the assumption of the top-down relation.

The link to economic theory for the factor demand relation is weakened if other factor inputs are merely adjusted in proportion to the adjustment in energy input. Another solution is to characterise the difference in energy input demand between the top-down

[3] See Chandler (1994), for examples of links from economic variables to bottom-up models

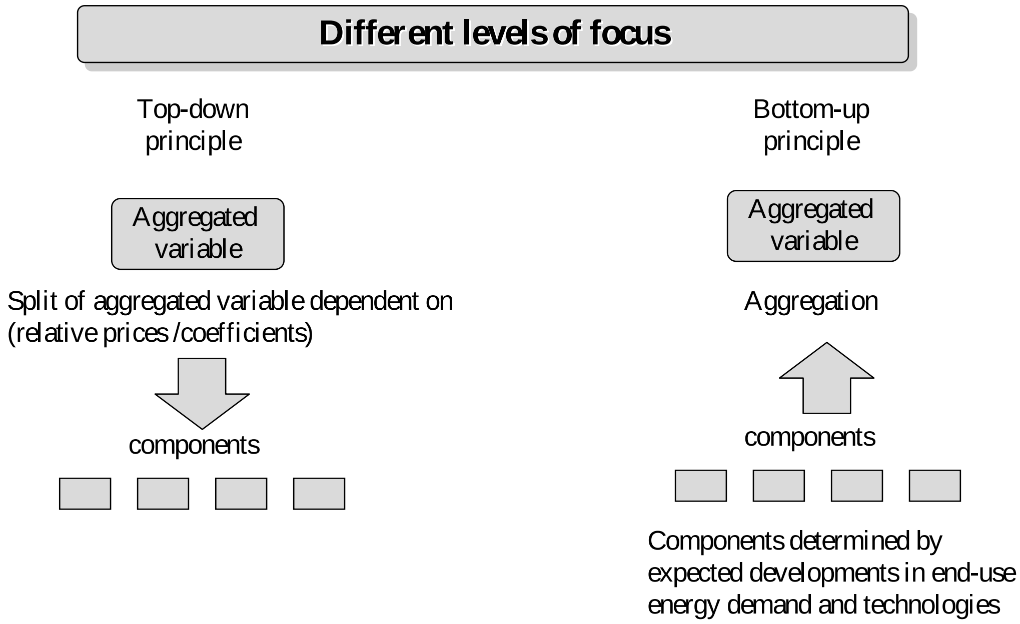

Figure 1 Aggregation level for relations determining, e.g., energy demand

and bottom-up models as an efficiency development. The top-down model determines the demand for input of energy services and the actual energy demand is found by adjusting for the development in energy efficiency.

A mixed principle for integration implies that:

- The theoretical basis for the macroeconomic structure and economic behavioural relations will be unaffected
- Adjustments in the macroeconomic setup can be limited to a few relations with energy content
- Price and production effects in energy demand will still be present though of reduced importance relative to a top-down based integration
- Aggregation will differ even in the description of energy

A combined model integrating the two approaches with both price and income effects in a bottom-up model and with linking of the energy supply sector to the rest of the economy will provide a better description of energy issues, policies and their consequences for the overall economy. Thus a combined model will be able to analyse more complex issues incorporating both regulation of the energy supply sector and households along with energy tax policies including the interdependencies between the energy system and the economy.

Some studies have worked along this idea and integrated the approaches by linking bottom-up and top-down models. A widely used model of this kind is MARKAL-MACRO (Manne and Wene, 1992). This model is an integration of the bottom-up optimisation energy model MARKAL, which has been used for several years, and a specially designed MACRO model. Other integrated approaches for the energy supply sector include GLOBAL 2100 (Manne and Richels, 1992); in a long-term growth model this incorporates an optimisation between energy technologies, which are to be made available at some time in the future. The model for Denmark described below lies within this integration approach but involves other types of top-down and bottom-up models than the integrated models mentioned above.

Integration according to a mixed principle is used here as it creates the most flexible model structure and can be designed to minimise the re-specification and re-estimation work. Flexibility arises from the possibility of including bottom-up modules or excluding them, whereby the different effects from using bottom-up modelling or top-down modelling for elements of energy demand and supply can be examined. Different types of bottom-up modules linked to the top-down model can be compared as well. A mixed principle also allows concentrating on the important parts of energy demand and supply without having to change the top-down model specification in many areas, which could have made necessary a huge amount of re-estimation and reformulation work.

An important reason for choosing a mixed principle is that bottom-up modelling of energy demand is seen to be much more important and relevant for some parts of energy demand than for others. Top-down specifications are more inaccurate for sectors where technical energy parameters are very important for determining energy consumption and these parameters change at uneven rates, for example, where the change occurs only by replacing long-lived production capacity or by adding new vintages of electric appliances.

4. Model description

The integrated model called Hybris[4] consists of the macroeconomic top-down model ADAM and three bottom-up energy modules. Integration of bottom-up and top-down elements is the result of a mixed principle. Links between the bottom-up modules and ADAM have been established and the system is run in an iterative procedure.

Integration of the energy modules and ADAM was established through a number of links. Links have been identified from the top-down model, which means that the bottom-up modules have to aggregate or disaggregate variables to fit the specification of the macro model. The structure of the macroeconomic model ADAM was kept unchanged.

Bottom-up principles were applied to three specific bottom-up modules

- Energy supply (electricity and heat)
- Electricity demand in households
- Heat demand in households

[4] Hybrid Integrated Simulation model

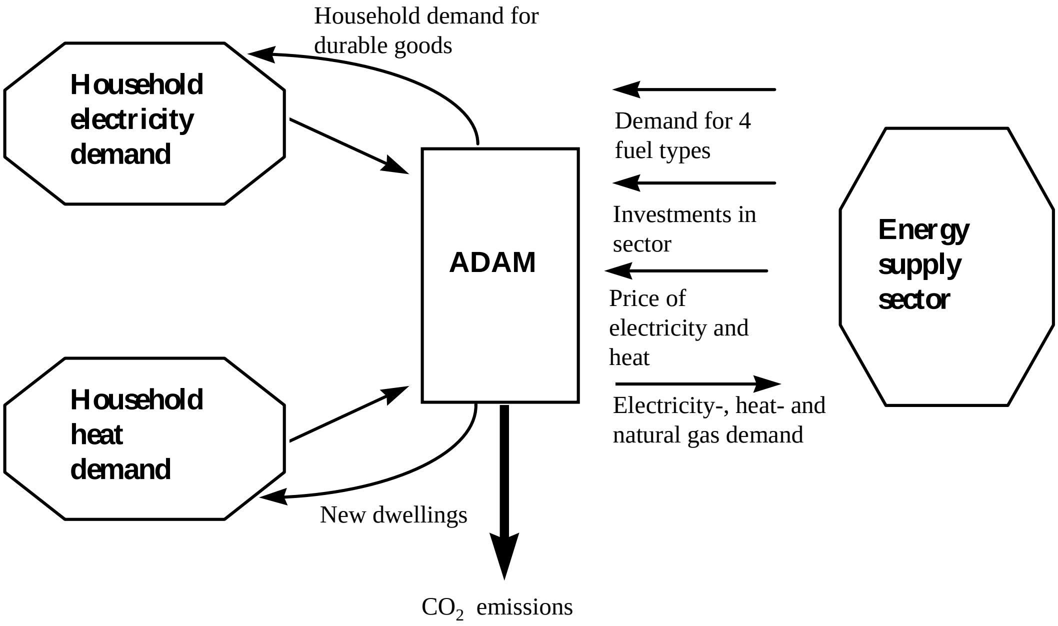

Figure 2 Model structure in Hybris

The energy supply sector was chosen to follow bottom-up modelling practices based on the importance of this sector for fuel demand and emissions in Denmark. More than 50% of CO_2 emissions in Denmark can be attributed to this sector. The long-term investment horizon, the detailed regulation and the limited number of production units also make this sector relevant for a bottom-up description. At the same time top-down modelling of the sector is very rude. In ADAM the sector is modelled with constant shares of two fuels: coal and fluid oil products that include natural gas. Thus, there is no fuel substitution in the energy supply sector in the basic ADAM model. In the bottom-up module price induced fuel substitution among four fuels: coal, fuel oil, natural gas and biomass is very important and can create substantial changes in CO_2 emissions.

Electricity demand in households was chosen because it is one area of modelling where bottom-up modelling does not incorporate price or income effects. Price and income effects could be very interesting to incorporate in some of the exogenous developments of, for example, appliance stocks. Household heat demand was found interesting for the same reasons as for electricity demand and because it constitutes the other part of the relevant consumption group in ADAM. Household heat demand is regulated in Denmark and related to the expansion of networks for district heating and natural gas. The household energy demand modules are also areas where bottom-up modules have a long tradition in Denmark and have been extensively used for energy planning.

The modules include economic behaviour, which is an important factor in determining the fuel demand in the module for electricity and heat but is much less important in the household modules. Household modules are linked to economic variables driving the sales of appliances and the total heated area. Integrating the bottom-up modules with ADAM was established by creating a number of approx. 100 linking variables and running ADAM and the modules in an iterative procedure. Linking variables include: energy demand, fuel prices, input coefficients, investments, tax revenues, stock variables, etc. Some of these are important variables determined in either the bottom-up modules or in ADAM, but others are chosen merely to ensure consistency between exogenous assumptions. The important links in Hybris are:

- Electricity and heat prices
- Fuel demand in the energy supply sector
- Electricity and heat demands in households
- Electricity, heat and natural gas demands in the economy
- Investments in electricity production capacity

Electricity and heat prices are the most important for the effect of linking from the energy system to macroeconomic variables. Higher prices lead to increasing production costs for industry and a deteriorating competitive position in foreign markets. The major parts of macroeconomic consequences from changes in the energy system or energy prices can be referred to this link. Fuel demand influences the trade balance, but the size of fuel consumption changes in the energy supply sector is relatively small compared to other factors that influence the trade balance.

The energy supply sector in ADAM is replaced by the developed bottom-up module by transferring ADAM variables from the bottom-up module to exogenous variables in ADAM. This is possible, due to the flexible possibilities for exogenising relations in ADAM. In Figure 3, links between ADAM and the energy supply sector are illustrated. Demands for electricity and heat are determined in ADAM, where household demand is indirectly determined in the two other energy modules.

It is the energy supply sector which is the most obvious sector to describe with a bottom-up model without constant fuel price elasticities. At the same time, it is relevant to include some fuel demand responses to fuel price changes. Short-term responses (within a year) will depend on the technology used in the production capacity at the time of price change, which could be very well described in a bottom-up model that includes cost minimisation. Long-term fuel price effects depend both on the organisational structure of the energy supply sector as well as on vintage effects of existing capacity. Direct regulation of the sector could be the driving force for long-term fuel changes, but if the sector is moving towards deregulation the fuel price will become a more important parameter for long-term fuel demand changes.

The module developed for Hybris covering the energy supply sector is a bottom-up module as it includes a very detailed description of the major plants in Denmark with technical parameters for energy conversion efficiency, fuel substitution limits on individual plants, plant capacity, lifetime and co-generation parameters. Top-down elements represented by prices are also very important in determining fuel demand in this module. The energy supply module is in itself an example of integration of bottom-up and top-down approaches to energy-economy modelling.

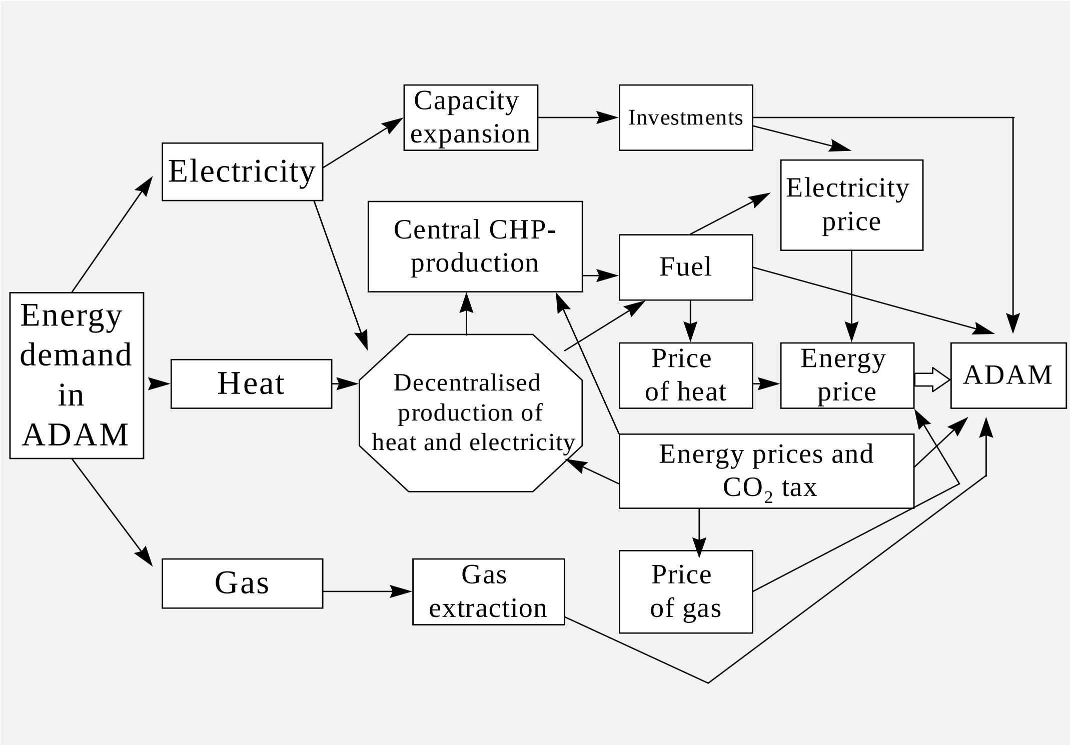

Figure 3 Links between the economy and the energy supply sector

Fuel input for electricity and heat production by the major combined heat and power plants in Denmark is found by minimising total fuel cost for these plants. Substitution between fuels within boundaries specified for each plant is allowed in minimising production cost. Fuel input to electricity and heat production is found by minimising total fuel cost for the joint production of electricity and heat by the 50 major power plants of Denmark, which are mainly combined heat and power plants. Substitution between fuels within technical constraints specified for each plant is allowed in minimising production cost. Fuel demand from each plant is found based on a duration curve for electricity demand. The duration curve for electricity is based on the assumption of 365 identical 24-hour periods and use of a linear approximation. The duration curve illustrates the time in which electricity demand is at a certain level. Heat is assumed to be storable within the 24-hour period to the extent necessary, and no duration curve for heat is applied here.

Plants are sorted according to marginal costs given the cost-minimising fuel mix on each plant. Thus, substitution between plants with different production cost takes place within limits given by the duration curve. The plants with the high marginal costs (fuel costs) will produce relatively less, but as long as the peak demand includes their capacity they will produce. Secondary units that are nearly 20% of production at present are treated as exogenous. An exogenous capacity projection and exogenous number of full load hours are used to calculate production. Expansion technologies for these plants are handled as exogenous but technical parameters change over time and the endogenous expansion of production capacity in large plants acquires the technical parameters given by the year they are built.

A detailed description of the electricity-pricing policy formation is included following the official guidelines given by Danish legislation. In principle, prices are given by average cost as the utilities are not allowed to generate surplus. Important and fluctuating parts of the cost determination for electricity prices are fuel costs and especially allowances on production capacity under construction. Fuel costs change as a consequence of substitution induced by fuel taxes and as new capacity includes options for using different fuels. The total investment cost of large power plants can be written off in only 5 years during construction where the physical lifetime tends to be 25-30 years. By this legislation Danish consumers directly and immediately pay for construction of new plants. This creates fluctuations in electricity prices with rising energy prices in the years prior to the introduction of new power plants and falling electricity prices following the introduction. The module includes an option to change the price relation towards short-term marginal cost pricing. Investments in electricity production capacity are calculated from the expansion of capacity and are linked to the investments of the energy supply sector of ADAM. Substitution possibilities are present in the existing Danish capacity primarily as an option for switching between coal and fuel oil and to some extent natural gas. The scenarios and their results reported later in this paper assume that future production capacity expansion is dominated by multi-fuel combined heat and power plants. This implies the possibility of substituting between using as much as 50% biomass in each new plant or almost 100% coal or fuel oil.

Household heat demand is described from a net heat demand per square meter heated area and new dwellings from ADAM increase the heated area. Thus, the income effect on household heat demand arises indirectly through the demand for new dwellings. The shares of heating technologies are projected according to official energy plans. Projected are the local efficiencies of different heating technologies, both technologies such as natural gas and district heating as well as individual heating technologies such as those based on electricity, biomass, coal and oil. In the module for household electricity demand a number of electrical appliances are described regarding electricity consumption and the coverage percentage (penetration ratio) in households of each appliance. The stock of appliances is derived from a proposed pattern of coverage development. The speed at which this development takes place is dependent on the activity of households in buying consumer durables, which is the important link to the economy in this bottom-up module.

5. Properties of the integrated model relative to bottom-up and top-down models

The properties of Hybris are different compared to the bottom-up modules and ADAM, because Hybris includes the interactions between the models. This is especially seen for the strength of energy and emissions response to emission-reducing initiatives. Another result of integrating is that the effects of initiatives depend on which other initiatives are carried out at the same time. In many cases of experiments with Hybris this leads to less reduction than anticipated by analyses carried out with separate models and for separate initiatives.

The most important properties originating from integration of top-down and bottom-up in Hybris include:

- The effect on electricity prices and electricity demand as a consequence of regulating fuel mix and capacity expansion technologies spill over to the energy demand in top-down relations.
- Changing macroeconomic conditions affect the energy system structure and feed back to the economy through changing energy prices and investments.
- Energy price elasticities are relatively low in top-down relations for industrial energy demand, very low in household energy demand and at some points very high for the energy supply sector.
- Economic costs of emission-reduction initiatives arise through price effects which are scarcely more than marginal when analysing taxes imposed on all energy use. Macroeconomic costs seem very moderate for all kinds of reduction initiatives.

Fuel price effects are more important in Hybris than in both the macroeconomic model ADAM itself and particularly in traditional bottom-up models, where price effects play a minor role. The increased price effect originates from the high degree of fuel substitutability in the energy supply module and is primarily connected to the choice of fuel inputs in electricity generation. The fuel price elasticity in this module is far from constant as is often the case in macroeconomic models. It is very hard to find econometrically reliable relations for fuel demands in the energy supply sector, which sometimes force macoeconomic models to exempt fuel substitution in the sector by distributing total fuel demand on fuel types by coefficients.

Economic growth is still the driving force behind the energy demand growth. An integrated model such as Hybris could be expected to show that economic growth and energy consumption are only slightly connected. The actual interdependence between these variables in Hybris is very high as energy demand is growing roughly in line with the economy. Both household demand for electricity through the buying of durable consumer goods and household heat demand through the investment in housing area respond to changes in income.

Hybris is capable of analysing a long range of traditional bottom-up and top-down energy options in the same setup. The possibilities include:

Top-down

- Effect of taxation on fuel inputs in the energy supply sector with constraints originating from the changing production structure
- The effect of economic growth on energy demand and the capacity structure of the energy supply sector

Bottom-up

- Regulation of fuel mix and capacity expansion in the energy supply sector
- Effect of regulating energy use in new household appliances

Hybris does not include substitution between different fuels in industrial demand. This reduces the effect on emission from CO_2 taxes compared to other top-down models. Fuel substitution in industry has been covered by a parallel project reported in Møller Andersen and Trier (1995). The transport energy demand has not been handled separately in Hybris, which means that it is the top-down description from ADAM that is included in Hybris. Obviously, a bottom-up approach with some saturation effect in the private car intensity of the population would yield different results. In Møller Andersen and Trier (1995) a thorough treatment of transport energy demand from both households and industry is carried out and top-down satellite models to ADAM are constructed but without feedback to the macroeconomy.

Emissions in Hybris are calculated from the macro model aggregation level with only three fuel types, which contributes to some inaccuracy in the calculation of total CO_2 emissions. This is a consequence of the different aggregation of energy demand in different parts of Hybris, which is caused by the mixed integration principle. Calculations of emissions have to be performed at the least disaggregated level for fuels that is found in Hybris. The model setup is designed to be run with or without the bottom-up modules for electricity and heat demand in households. In this way different properties of the bottom-up descriptions of households and the corresponding description in the top-down specification can be analysed. The main results from including the bottom-up modules for household electricity and heat demand are:

- CO_2 tax effects on emissions are moderated when bottom-up modules which have very low price elasticity are included.
- The high income elasticity in the top-down specification of household energy demand is moderated as bottom-up modules describe how coverage of electricity-intensive appliances reach saturation.

6. Combining initiatives to reduce CO_2 emission

An integrated model such as Hybris takes explicit account of the interactions between regulations of the energy supply sector, e.g. restricting new capacity to a specific fuel mix and the related change in demand for electricity due to the resulting price changes. Combined initiatives were analysed using Hybris, and the effect on energy demand was less than the effect that was found by adding up emission effects from the respective initiatives and models. A CO_2 tax, regulation of fuel demand in the energy supply sector and regulations of household and industry energy demand were analysed in a combined scenario using the Hybris model. Results from Hybris of separate initiatives to reduce emissions and the combined initiatives are shown in Table 1.

Some characteristics of the interactions in the combined scenario were:

- Energy taxes had the full effect in industry energy demand, but the substitution effect

Table 1 CO_2 emission reduction from different initiatives

Analysed initiative	5 years	10 years	15 years	25 years
a) CO_2 tax	7.3%	3.8%	8.9%	13.9%
b) Regulation of electricity production	1.3%	1.5%	2.6%	7.6%
c) Demand side regulation	5.3%	7.6%	10.3%	15.9%
a) and b)	8.2%	5.6%	10.9%	15.6%
a), b) and c)	11.9%	12.5%	17.7%	27.4%

in the energy supply sector was less than if there had been no regulation on fuel mix.

- The effect of reducing household energy demand if electricity and heat production were already cleaner was less than in the base case for electricity and heat production.

The different categories of reduction initiatives represented in Table 1 are very dependent on each other. A CO_2 tax incentive in a) is the typical option analysed in a top-down model setup, where b) and c) are options which are analysed in bottom-up energy models. The initiatives examined in Table 1 are:

a) A CO_2 tax on all applications rising from 200 DKK pr. ton of CO_2 initially to around 400 DKK pr. ton in 25 years.
b) The electricity production sector was restricted to using biomass and natural gas on the production plants that were technically able to substitute. Wind energy was expanded further.
c) Demand side regulation including norms for the maximum electricity consumption of household appliances for sale.

The combined effect of a) and b) is only slightly smaller than the sum of a) and b) up to 15 years. At 25 years horizon the marginal effect of b) is less than 1/4. As option c) is added to the calculation of a combined initiative the marginal reduction effect is less than 3/4 of the effect of option c) alone. CO_2 reduction initiatives should not be analysed without considering other reduction policies, as the interdependencies between policies are quite significant as seen in Table 1. It is noticeable that traditional top-down and bottom-up initiatives in this integrated model are dependent on each other, but they do not fully offset the effect of one upon the other.

In Figure 4 the emission effect of the combined initiative a), b) and c) is shown. The peculiar time profile is caused by the technical constraints in the electricity production system and substitution between fuels on existing capacity. The fuel substitution possibilities are increased as old electricity and heat production capacity is replaced with flexible multi-fuel plants.

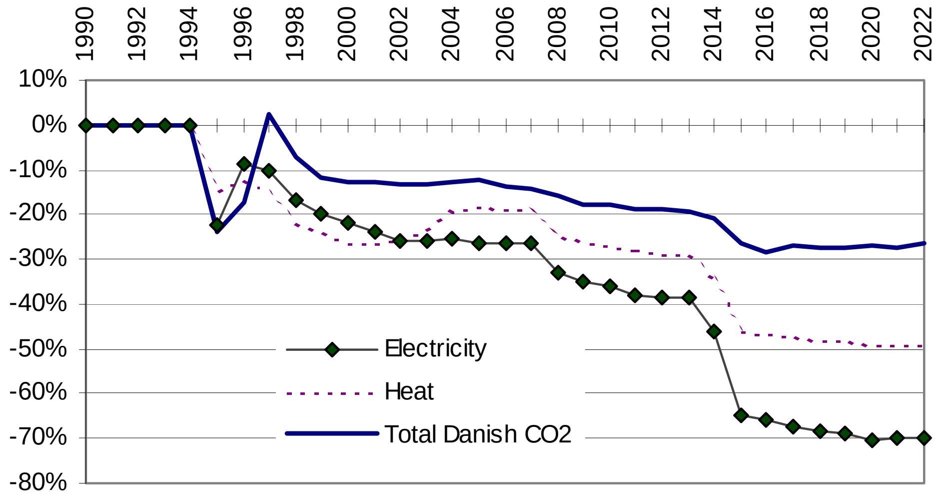

Figure 4 CO_2 emission reduction by a combined initiative

The first reduction in emission to be seen in the graph occurred when coal was replaced fuel oil and natural gas. A few years later the relative fuel price movements induced a shift back to coal from fuel oil. In the long run the CO_2 tax and restriction on technology for new production capacity led to a shift towards renewable energy sources especially biomass. The reduction in emissions from end use energy demand was much more stable than the emission effect from electricity and heat production.

In the Hybris model the emission reduction possibilities in the energy supply sector are very great seen from the point of the present situation in the sector. With the given development in world fuel prices the emission reduction in the sector could be reached with a moderate CO_2 tax and regulation of the technologies with which the production capacity is expanded. Further reduction in this sector is not possible without expanding renewable technologies even further or replacing plants within their remaining physical lifetime. This conclusion is based on the technologies available in this scenario which consisted only of proven electricity production technologies with a constant yearly improvement in technological parameters.

7. Concluding remarks

The purpose of this study was to integrate bottom-up and top-down approaches to energy-economy modelling by linking models for Denmark based on these approaches. This study shows that a model integration is possible where most of the characteristics and possibilities of bottom-up and top-down models are included. A mixed principle for integration which was used here could lead to a weakening of the degree to which relations are theoretically founded.

However, with the macroeconomic model used in our case (ADAM) the linking and replacement by bottom-up specifications influenced the macroeconomic theoretical basis only slightly.

The properties of the linked model include wide possibilities for analysing very different options for reducing energy consumption and emissions. Options included in traditional bottom-up and top-down models could be analysed in our linked model taking into account the interactions between energy and economy and the different initiatives. The most important links between the energy supply sector and the macroeconomy were found to be the price of electricity and heat, and to some extent the investments in the energy supply sector.

The relative unproblematic integration of top-down and bottom-up models in our case relies on both the integration principle chosen and the respective models which have been integrated. It was chosen to integrate approaches in the most unproblematic fields by introducing bottom-up modelling of energy demand for: the energy supply sector, household heat demand and household demand for electricity. Further, it is worth noting that the different reduction initiatives analysed here do not seem to be complementary between bottom-up and top-down initiatives but there exist important interdependencies between them leading to lower marginal effects of the initiatives if combined. At the same time, the emission reduction effect of individual initiatives evaluated in an integrated model such as Hybris are larger than the effect found in separate top-down and bottom-up models.

Acknowledgements

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Taxing CO_2 and subsidising biomass: Analysed in a macroeconomic and sectoral model*

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department, Box 49, 4000 Roskilde, Denmark

ABSTRACT

This paper analyses the combination of taxes and subsidies as an instrument to ensure a reduction of CO_2 emission. The objective of the study is to compare recycling of a CO_2 tax revenue as a subsidy to biomass use as opposed to traditional recycling like reduced income or corporate taxation.

A model of the energy supply sector of Denmark is used to analyse the effect of a CO_2 tax in combination with using the tax revenue for subsidies to biomass. The energy supply model is linked to a macroeconomic model such that macroeconomic consequences of tax policies can be analysed along with consequences for specific sectors as agriculture. Electricity and heat are produced at heat and power plants and utilising fuels which minimise total fuel cost, while the authorities regulate capacity expansion technologies. The effect of fuel taxes and subsidies on fuels is very sensitive to the fuel substitution possibilities of the power plants and consequently the extent to which expansion technologies have been regulated.

It is shown how a relatively small CO_2 tax of 15 USD/tCO_2 and subsidies to biomass can produce significant shifts in the fuel input-mix, when the expansion of production capacity is regulated to ensure a flexible fuel mix. The main finding is that recycling to biomass use will reduce the level of CO_2 tax necessary to achieve a specific emission reduction. Policies to ensure a more intensive use of such relatively expensive renewable energy sources as biomass could be implemented with only small taxes and subsidies.

Keywords: Taxes and subsidies; Fuel substitution; CO_2 reduction

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1. Introduction

The objective of this study is to compare targeted revenue recycling in favour of biomass (to sectors where fuels are very substitutable) to more traditional forms of revenue recycling in macroeconomic models.

The energy supply sector is very important in any analysis of emissions and options for reducing emissions. In the Danish case the CO_2 emission from this sector today accounts for more than 50% of total emissions. Traditional top-down analyses of tax-incentives to reduce emissions have not been directed at analysing special conditions in the energy supply sector. Long-term analyses have been carried out with emphasis on the energy supply sector and the investment decision between technologies based on different fuels. Medium-term capacity constraints and related constraints on technology as fuel substitution possibilities in this sector are important factors with respect to analysing CO_2 tax policies. Price elasticities are far from constant and could be even infinite as substitution possibilities for switching fuels at short notice could be large on existing production capacity. In the Danish case a considerable share of electric power plants can switch fuel between fuel oil and coal from month to month or even on shorter notice. The policy adopted for technological implementation in new production capacity might increase the number of fuels among which the plants are able to substitute in the future. Multi-fuel plants have investments cost only slightly higher than the traditionally build coal fired plants in Denmark. The flexibility regarding future price developments or changing environmental constraints might heavily outweigh this extra cost.

Substitution possibilities in the Danish power sector are modelled in detail in a project carried out on integrating top-down and bottom-up modelling approaches. This project is reported in Jacobsen et. al.[6] and Jacobsen[7]. The energy supply sector and specially the power sector is modelled in detail including the links which exist to the macroeconomy and the links from the macroeconomically determined demand for electricity and heat. Unlike most bottom-up studies that do not include price induced feedback effects on energy demand (Chandler[1]) the model used here through the link to a macroeconomic model and an iterative procedure takes explicit account of this interaction with economy.

Taxes and subsidies on fuels used in the energy supply sector can be analysed in this model set-up, but the model is not suitable for analysing fuel substitution and the subsidising of certain fuels in the rest of the economy.

Biomass is treated as an important fuel alternative and is seen as one of the policy options with respect to the technologies that are relevant to include when expanding or replacing power production capacity. The link with the economy is included both with respect to the biomass demand and the effect on the total macroeconomy, but there is no description of the supply side of biomass in the model used here.

2. Model description

The model of the energy supply sector is a bottom-up based simulation model with many technological parameters. The model also features important top-down elements, e.g. running production cost of electricity and heat at the large plants are minimised given fuel prices. The minimisation is carried out with respect to the demand given from the macroeconomic set-up and capacity and technology given by existing capacity and policy-determined capacity expansion characteristics.

Links between the energy supply sector and the macroeconomy have been established and the energy system is this way an integrated part of the macroeconomy. The macroeconomic set-up used is ADAM (Annual Danish Aggregated Model), which is an econometric based keynesian type of model and the most common used macroeconometric model in Denmark. It is only the energy supply sector in ADAM that has been replaced by the bottom-up module of energy supply described in detail below.

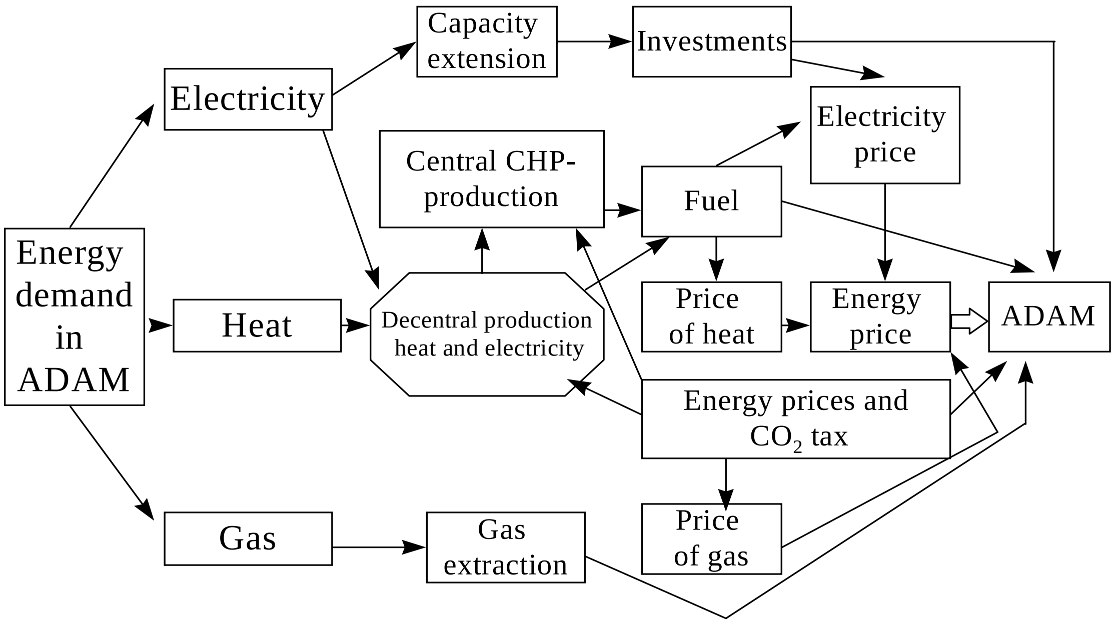

Figure 1. The energy supply sector and its links with the macroeconomy

The authorities have traditionally regulated the Danish power sector and this is reflected in the model in different planning and regulatory elements. The expansion of electricity production capacity based on renewable energy sources is directed by policy and the expansion of this production category is regarded as exogenous in the model. Wind power, decentral combined heat and power plants and industrial co-generation are all handled in this way. Only the expansion of capacity by the major utilities is related to electricity demand.

Production capacity is expanded according to a target of 20% reserve production capacity at peak levels of domestic electricity demand. It is the capacities of the large central power plants that have to be adjusted to reach the target. The model includes the possibility of handling the import and export of electricity given the transmission capacity and fixed import and export prices, which are not necessarily at the same level.

Much of the Danish energy supply system is based on combined heat and power production and the model include a detailed description of the co-production problem.

The model includes a load curve for electricity demand but heat demand is taken as total yearly demand; no account is taken, however, of the geographical restrictions on heat demand that are quite relevant in the Danish case.

The secondary capacity of wind power, decentral combined heat and power and industrial co-generation are all producing at their capacity but with an exogenous number of yearly production hours. The primary production capacity faces a residual electricity and heat demand. Production is allocated to individual plants in the primary system from a minimisation of production cost of the given heat and electricity demand and from a duration curve of electricity demand. All primary production plants are described with their technical characteristics as: fuel mix and substitution boundaries, fuel efficiency, heat capacity, factor of electricity loss to heat produced and the remaining physical life time.

A detailed description of the Danish electricity and heat production system is important for analysing the medium- term options in the system. With a horizon of up to 15 years any kind of analysis of CO_2 emissions, taxes and subsidies will be very dependent on the existing production technology of electricity and heat production. This is certainly the case in Denmark, where the system is characterised by slow growth of demand and some excess production capacity at present. Further, the expansion of secondary production capacity postpones the introduction of new technology with increased flexibility and fuel substitution in the primary electricity and heat production sector.

Price determination is an important element of the link between the energy supply sector and the macroeconomy. The price of electricity is determined from the cost of producing and distributing electricity. Fuel cost, other material inputs, labour cost, appropriations and depreciation are included following the requirements of the Danish legislation.

Danish legislation precludes the existence of profits in the power sector. This mean that any profits of the total production and distribution system must be returned to consumers by adjusting the electricity prices the following year. This is included in the model as a no-profit rule. Other features of Danish legislation are the very favourably conditions for appropriations connected to investments. In the five-year construction period of large power plants 75% of total construction cost can be appropriated and thereby included in electricity prices. Consumers hereby pay investments in the production and transmission capacity of the power sector in advance. The model takes account of this relation as well.

The price of electricity responds to changes in fuel prices including taxes and subsidies. Through the link to the macroeconomic demand for electricity the response in demand is fed back to electricity production. Thus the effect of taxes on fuel consumption in the power sector includes two effects: substitution between fuels in the power sector and a reduction of electricity demand from the macroeconomic part of the model.

Properties of the energy supply model relevant for analyses of taxes and subsidies include:

- Infinite substitution between fuels at relative trigger prices for the individual plant.
- Segments of power sector without substitution.

- Policy-dependent development of future substitution possibilities through the distribution of new capacity on different technologies.
- Electricity demand development influencing electricity capacity expansion speed and thereby the introduction of technologies with substitution possibilities.
- Effects on biomass production, economic growth and foreign balances are found.
- The substitution options and technological characteristics of electricity and heat production are very dependent on the time pattern of the scrapping of existing production capacity.

The important links between energy supply sector and macroeconomy are: electricity and heat prices, investments, fuel demand and the feedback from the macroeconomic determined electricity and heat demand. Changing economic conditions have important impacts on the energy supply sector. In the short run demand for electricity and heat determine production and in the long run demand determine power and heat capacities. Price of expanding production capacity is dependent on the price for investments determined in the macroeconomy. In the Danish power sector wages and other inputs apart from fuel accounts for about 75% of total costs and thus the output price from the energy supply sector is highly dependent on the general price level of the economy.

Effects from the energy supply sector on the economy are of less importance for the macroeconomy than the effect from economy to the supply sector. The main influence on the economy is seen from the output price of the energy supply sector. However, the direct impact of changes in fuel prices and taxes is more important for the economy than the effect, which is seen through the energy supply sector as the fuel costs only account for 25% of total costs in the sector.

3. Substitution

For all analyses of price incentives for reducing CO_2 emissions the substitution possibilities between fuels are vital. For the power sector substitution options can be relatively well described. An econometric analysis of substitution in the sector would hardly yield reliable results for substitution possibilities or fuel price elasticities. Many econometric specifications would include constant elasticities, which is certainly not the case in a sector where technological differences are relatively small between producers and the corresponding relative trigger prices of fuels do not differ much.

In a CGE model study of the Danish economy (Frandsen et. al.[3]) the energy supply sector is modelled with substitution between aggregates of energy, capital and labour but without substitution between fuels.[1] Substitution is recognised to be relevant in the power sector between coal, natural gas and fuel, but this substitution possibility is not included in the model, as this would require modelling of the relevant trigger prices. The bottom-up characterised energy supply model used here include a detailed description of technical parameters which in an endogenous way determine the trigger price for each individual production unit and the corresponding substitution between fuels.

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[1] In a following version of the model (Frandsen et. al., [4]) substitution between fuels have been estimated and included in the model for most industries, but not for electricity and heat.

In the model fuel substitution on each plant is described as taking place immediately as relative fuel prices changes in favour of another fuel. "Immediately" is used in the sense that we operate on a yearly basis.

Substitution in the model takes place through different channels, as listed below:

- Substitution between fuels in the individual plant.
- Substitution between plants with different fuel mixes and fuel costs.
- A policy determined substitution between fuel technologies in new and old production capacity.

The first possibility is the most important if the system already includes technology options for substitution between fuels. If substitution is limited in the existing system the policy option for regulating fuel technology is more vital.

In the existing capacity substitution takes place at the individual plant level, where the cost-minimising fuel mix is chosen within the technical boundaries for each specific plant. At the central combined heat and power plant level the production of each plant is determined by a marginal production cost and a load duration curve for the production that has to be delivered from the central part of the system. Substitution between plants with different fuel mixes takes place by decreasing the running hours of the plants with increased relative fuel cost and increasing the running hours for plants with decreased relative fuel cost. Policy-initiated fuel substitution (apart from taxes) is found in the way that substitution possibilities in the longer run are highly dependent on the fuel technology options of new plants and dependent on the mix between the expansion of renewable energy based production capacity as wind power and traditional production capacity.

Substitution possibilities are present in the existing Danish capacity mainly in the form of switching between coal and fuel oil and to some extent natural gas. The scenarios and their results referred to here assume that future production capacity expansion is dominated by multi-fuel combined heat and power plants. This implies the possibility of substituting as much as 50% biomass use in each new plant or almost 100% coal or fuel oil.

4. Taxes and subsidies

Taxes as an incentive to reduce energy consumption or the composition of energy demand on different fuels have often been analysed in a top-down context. In here the application of taxes as a CO_2 tax is examined with respect to total society, but including a very detailed modelling of the energy supply sector with many bottom-up characteristics. The approach of this model implies that substitution between fuels are modelled in detail in the energy supply sector which is the sector that has the highest CO_2 emission and substitution possibilities in the Danish case.

Taxes and subsidies could be compared to direct regulation of fuel use for individual plants in the power sector or regulation of the use of specific fuels for the entire sector. Cost of regulation in efficiency terms will be higher for direct regulation than for taxation. This theoretical assumption is used as an argument for the use of taxes on fuels in the way that the individual plant is thought to minimise production cost and thereby switching to a fuel mix, which is not necessarily the same as the fuels mix they are forced to have by the regulation.

The argument of higher cost of regulation is more valid for a sector with many individually optimising units than for a sector, which is centrally planned, and optimised. This mean that the argument is less relevant in the present Danish case of optimising the total system, but the relevance might increase as deregulation is implemented and the production structure becomes more fragmented.

An important point when analysing economic costs of CO_2 taxes is the recycle principle for tax revenues used in the macroeconomic model. As the top-down part of the model is the most convenient part to recycle economy wide tax revenues the most obvious choice is recycling by lowering general tax rates. The effect of this recycling depends heavily on the properties of the macro model in question. If the model used or the economy examined includes many distortionary taxes or imperfections an optimisation of the recycle principle towards specific tax rates or towards cost of labour and capital could improve the overall effectiveness of the economy. Hereby the negative impacts on GDP of CO_2 taxes could be reduced or even eliminated.

Often positive GDP or employment effects from recycling revenues are referred to as a "double dividend" from green taxes. As mentioned in Cline[2] it is difficult to explain why the political system is incapable of rationalising the tax structure in the first place and thereby achieve a second dividend. This leads to the conclusion of analysing primarily long-term production function effects of carbon taxes.

The different recycling principles are often seen as an integrated element of analysing emission reducing initiatives. Recycling effects on the economy that works through non-energy relations should not be seen as an effect of the emission initiative but instead as a consequence of the model used and the imperfections of the economy examined. Changing the tax structure, improving the labour market functioning or reducing other distortionary relations in the economy could in many cases achieve such recycling effects.

In a study on green taxes in the Danish case Frederiksen[5] use an empirical general equilibrium model to evaluate a wide range of recycling principles. The model used in this study shows the divergent results on economy from different principles, but as it is a general tax on business energy use that is analysed it is only general options for recycling to business as a whole that is analysed. In this study results of increasing energy prices by 50% range from a negative impact on the present value of GDP of 3% to 70%.

The question of recycling is important in all top-down analysis of costs of reducing emissions but is generally not acknowledged in bottom-up studies. Linking the two modelling approaches leads to a recycling in the top-down or macroeconomic part of the model, but the revenues determined in the macroeconomic part of a linked model might just as well be recycled in a bottom-up module which determines fuel demand in the energy supply sector.

In here the recycle principle is analysed with respect to the difference between an economy wide cutting of corporate tax rates and recycling of tax revenues from the energy supply sector to the sectors own use of a specific CO_2 low or neutral fuel as biomass.

Biomass use in Denmark including waste combustion constitutes around 7% of total energy consumption in 1997 and consists of the categories represented in Table 1. Total renewable energy corresponds to around 9% of energy consumption. In the official

Danish Energy Plan the share of renewable energy is expected to increase towards 35% in 2030, which is to be accomplished by increasing both biomass use and wind power. For biomass including waste an increase from 50 PJ to 145 PJ is assumed.

Table 1. Biomass use in Denmark 1997 and the potential for 2020 (TJ)

Resource	Total consumption	Electricity and heat production	Fuel share in electricity and heat	Potential resource 2020
Straw	13351	7426	1.7%	39000
Wood	21013	5625	1.3%	23000
- Wood chips	2703			
- Firewood	9603			
- Wood Pellets	2828			
- Wood Waste	5879			
Biogas	2394	1715	0.4%	31000
Waste Combustion	27631	26587	6.2%	24000

Source: Danish Energy Agency: Energy Statistics 1997 and Danish Renewable Energy Resources, 1996

To reach the 145 PJ additional biomass resources must be introduced. Energy crops on marginal land or land that lie fallow are estimated to have a potential of up to 65 PJ. Some of this will have to be realised to reach 145 PJ. In the simulations that are reported below the additional use of biomass is assumed to be mainly straw and energy crops.

Biomass especially straw and energy crops are expensive fuels compared to coal, fuel oil and natural gas. To increase the share either direct regulation or some kind of a subsidy is needed. This paper explores the possibility of using a CO_2 tax revenue to subsidise biomass use as an alternative to fuel independent recycling to the production sectors. A tax imposed on all applications of energy is introduced and two alternatives of recycling of revenues are examined in the model set-up described above.

a) A CO_2 tax of approximately 50 USD/tCO_2 and a recycling of total revenue to industry through a lowering of the corporate income tax rate.
b) A CO_2 tax of approximately 15 USD/tCO_2 and recycling of revenue from the electricity- and heat-generating sectors as subsidies to the use of biomass. Revenues from other sectors are recycled as in a).

The long-term results of the two alternatives are compared in Table 2 and Figures 2-5 illustrate time series for a number of variables.

In alternative a) the emission reduction is achieved by reducing final demand as represented by electricity demand in Figure 2 in combination with fuel substitution in the energy supply sector. Residential sector electricity demand is reduced relatively more than commercial demand as a result of a reduction in real income adding to the effect of sharp price increases. The commercial sector by the recycling of revenues is compensated for the cost-increase, which secures that production is only marginally reduced. Total electricity demand is reduced by 9% in alternative a) and by 4% in alternative b).

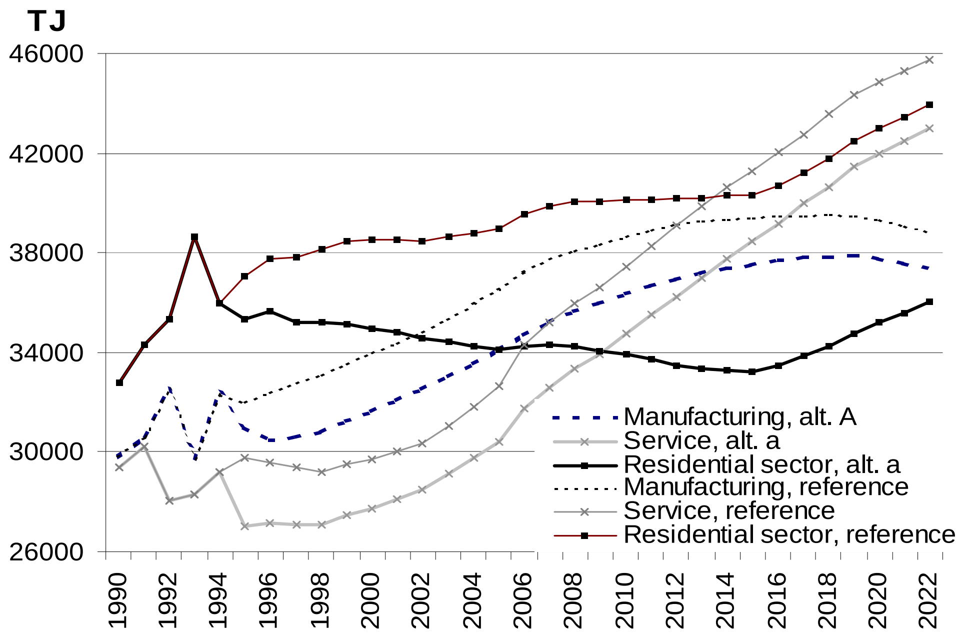

Figure 2 Electricity demand by sectors in reference and alternative a)

By imposing taxes and subsidies as in b) fuel cost are following a path as in Figure 3. The immediate fall in the price of biomass to zero is caused by the lack of substitution possibilities towards biomass. Only as new central capacity is build[2] the substitution possibilities arise and the subsidy effect on the biomass price decreases as the use of biomass increases.

[2] The reference case projects decentral capacity to rise from 1240 MW in 1995 to 2700 MW in 2020 compared to central capacity of 7702 MW in 1995 and 6800 MW in 2020. The decentral category is treated as exogenous because of the detailed regulation by Danish Authorities and the two policy alternatives use the same projection as the reference.

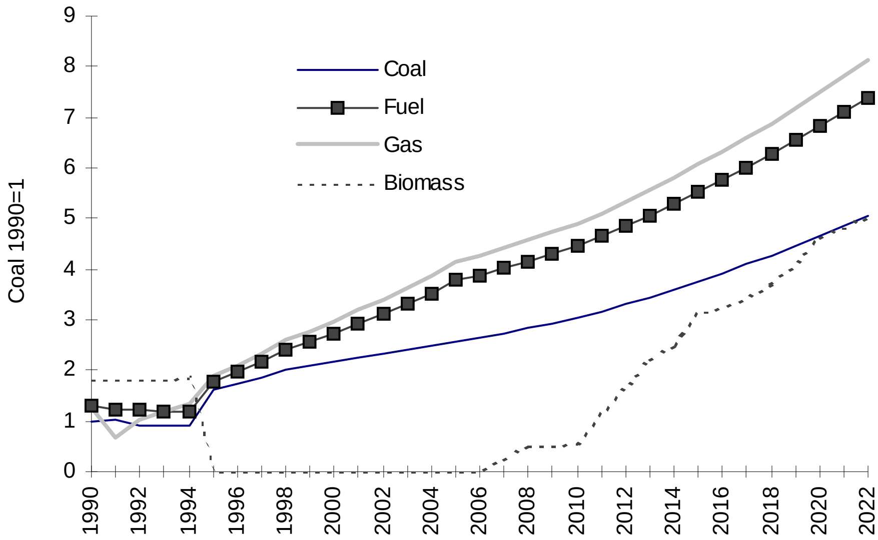

Figure 3. Fuel prices in alternative b) including taxes and subsidies

A CO_2 tax of 15 USD/tCO_2 as in b) is not high enough to initiate substitution from coal to natural gas or fuel oil. If the tax revenues were used for subsidising use of natural gas there would initially be substitution towards natural gas. But the underlying price projections (originating from an IEA scenario[3]) implies that in the long run taxes used for natural gas subsidising would not create substitution. All fuel used in the energy supply sector is subsidised both the price elastic and the inelastic part.

Prices used are nominal prices and including transport cost to the large power plants[4]. Biomass is a domestic price projection based on present straw and wood chips prices and inflated with the same rate as agricultural products in the macroeconomy.

[3] The rising fuel prices are from the 1995 projection of The Danish Energy Agency, which again are based on an IEA projection. Actual prices have shown lower growth for 1995-1998, but the present (1999) projection of the Danish Energy Agency follows a similar trend as the projection shown in Figure 3. The actual market price for biomass will be higher than in the figure as it is the input price for the power and heat producers that are included in the figure. The zero price only reflects that the revenue of the CO_2 tax is greater than the cost of the biomass used for a given year.

[4] No assessment of transport costs associated with biomass has been included. On average the transport cost used for calculations in Denmark constitute around 20% (3.2 DKK per GJ /18 DKK per GJ) of total biomass (straw) collection, transport and storage cost. This is for an average of 25 km. For wood transport costs are estimated to be higher based on longer average distances.

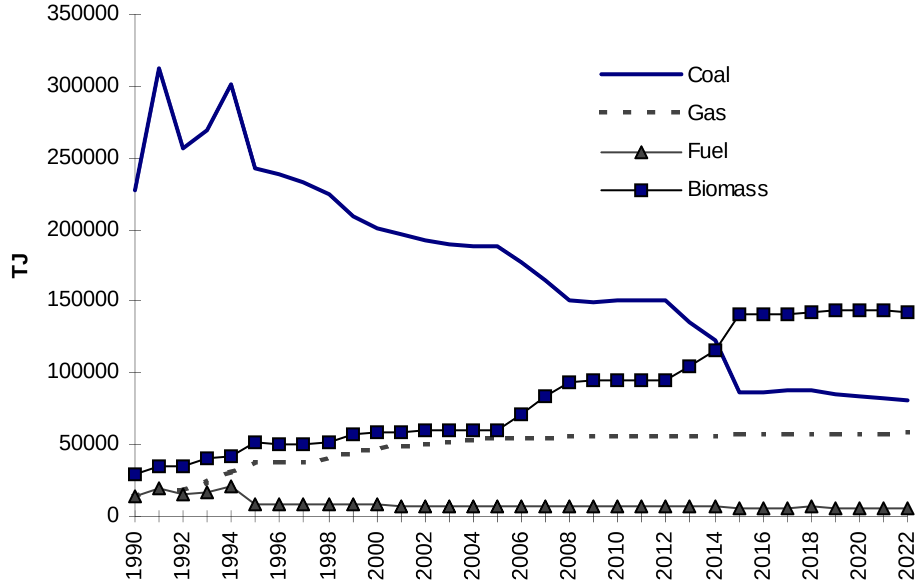

Figure 4. Fuels used for electricity and heat production with taxes and subsidies b)

In Figure 4 the development in the use of four fuels for the production of electricity and heat is shown. Coal is originally the main fuel used in the energy supply sector, but the share of coal decreases as biomass and to some extent natural gas increases. The first gradual increase until 2005 in the use of these two fuels comes from the secondary combined heat and power units and from production of district heat. Fuel demand from these units is inelastic, but tax revenues are used for subsidising their fuel as well. As technical substitution possibilities from 2005 and on increases, when old power plants are replaced with multi-fuel plants, the biomass use increases to the new limits. As the biomass use around 2020 reaches a considerable share of total fuel the tax revenue is not enough to subsidise biomass use to the technical limits of biomass use. This is reflected in Figure 3 where the cost of biomass converges to the price of coal. The final level of biomass demand in Figure 4 is below the level planned by the Danish Authorities (145 PJ) but it require that most of the potential resource for straw and energy crops on land that lie fallow is used. The price of biomass will be increased as volume increases, but the competition from imports off wood pellets or wood chips will tend to moderate price increases.

Table 2. A comparison of CO_2 tax revenue recycling: (effect at 25 years horizon)

Recycling	CO_2 emission	Electricity price	GDP	Agricultural production
Recycling through corporate tax a)	-16.0%	20.9%	-1.36%	2.7%
Recycling through subsidies on biomass etc. b)	-15.0%	3.6%	-0.36%	2.8%

The substitution towards biomass in the energy supply sector is of nearly the same size in a) and b). The necessary CO_2 tax to trigger this substitution is considerably greater in a) than in b), which leads to a GDP loss in a) that is three times the loss in a)[5].

The price of electricity will rise in both cases as total fuel costs increase as a result of the increasing use of the basically more expensive biomass. A falling electricity demand leads to higher unit production cost of electricity and gives another boost to prices.

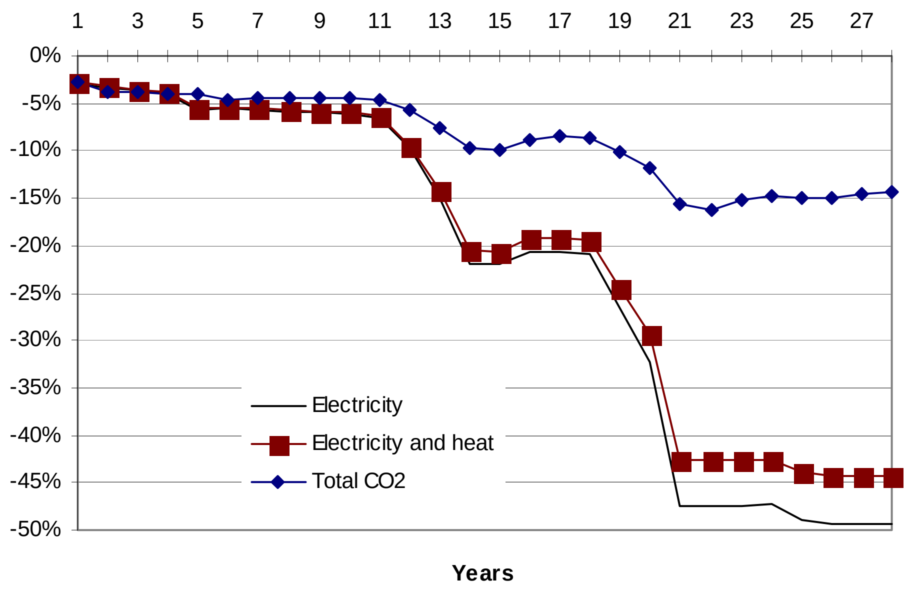

Figure 5. Emission reduction in alternative b)

In Figure 5 CO_2 emission in alternative b) is compared to a reference case/business as usual case. Emission related to the production of electricity is reduced the most compared to the reduction of total CO_2 emission, which is only reduced 15%. Substitution of fuels/the increase in biomass use for electricity and heat production accounts for ¾ of the reduction in this sector and reduced electricity and heat demand account for the last ¼ of the reduction. The substitution in electricity production is limited by technical constraints on production capacity, and in both our cases the substitution is bounded by these limits. In our model substitution between fuels is much higher in the power sector, than in other sectors, which means that price incentives are more effective in reducing emissions here.

The emission reduction that can be associated with electricity and heat accounts for about 85% of the total CO_2 emission reduction in both case a) and b). The last 15% can be attributed to reduction of final demand for other fuels. In case a) the substitution between fuels within electricity and heat production accounts for 66% of the total reduction in emissions and reduced final electricity and heat demand account for 19%. In case b) the reduction of demand for electricity and heat account for only 10% emission

[5] There is still a GDP loss because of an efficiency loss associated with changed input mix in industry in combination with a loss in international competitiveness following higher input prices, even though wages are lower. The compensation by reduced corporate taxes does not eliminate the loss of competitiveness.

reduction, whereas 75% of the reduction can be attributed to fuel substitution in the energy supply sector.

The economic costs of the two alternatives differ mainly as a result of the different tax levels necessary to achieve the same CO_2 emission reduction. A conclusion of this experiment with subsidies is that revenues from a CO_2 tax recycled as subsidies towards CO_2 low or neutral fuels in the energy supply sector have much greater reduction effect than other ways of recycling, such as corporate taxes.

It is important to notice that the reduction effect in the energy supply sector is different from the reduction in the rest of the economy. In this model set-up the reduction in energy conversion is a one-time gain if the trigger prices for the substitution towards the least CO_2 -intensive fuel is reached, where reductions in the rest of the economy could be increased almost in proportion to increasing energy prices.

The increased biomass demand in both of the above cases are assumed to be supplied from domestic resources. In the model used here the agricultural sector is the only supplier, and production in agriculture increases, but this sector includes both agriculture and forestry. Obviously, the production of biomass could to some extent substitute other agricultural products but the magnitude of this effect depends on how productive the land that is now used for biomass production once was for producing other agricultural products.

In linking from biomass demand to agricultural production biomass is seen as a by-product from agriculture as straw or as produced on unproductive or unused land. The underlying production cost of biomass will be dependent on the demand level from the energy supply sector, but in here it is assumed that the demand is kept within the limits of by-products from agriculture and forestry and thus a relatively constant price is assumed within the biomass demand range analysed here[6]. The positive effect of additional demand for agricultural products could be less in other types of macroeconomic model.

The findings can be compared to the results of Frandsen et. al.[4]. With the CGE model GESMEC for Denmark they find that a tax of approximately 50 USD/tCO_2 will reduce emissions by 25%. GDP will be reduced between 0.7% and 3.9% depending on adjustment cost especially associated with the stickiness of wages. If wages do adjust slowly the competitive position against foreign producers will deteriorate and the GDP loss will be greater. ADAM wages adjust relatively slowly so the GDP loss in alternative a) is less than the loss found with GESMEC. The reduction in alternative a) is less than in GESMEC mainly because elasticities in GESMEC are higher than in ADAM.

The basic characteristics of ADAM is important for the GDP cost of CO_2 taxes and with respect to the effect of recycling. However, the size of substitution elasticities can be more important for the emission effect of a given tax than the type of model. The result from targeted recycling (subsidies) to the use of biomass could very well have been obtained with another type of macroeconomic model if it was linked to an energy supply model with the same characteristics as the one applied in this paper.

[6] See also the comments to biomass volumes in Figure 4.

5. Concluding remarks

Analyses of CO_2 taxes as an instrument to reduce emissions have to take explicit account of the energy supply sector. A model as the one used in here could show the high reduction potentials from substitution between fuels in this sector, which can be achieved with only modest tax and minor implications for the macroeconomy. As the sector is characterised by high fuel substitution potentials the effect of recycling tax revenues within the sector towards the use of fuels that have low or neutral CO_2 content, e.g. the use of biomass as in our case, is quite high. Use of subsidies towards biomass have positive consequences for agricultural production in the model used here mainly as a consequence of assumptions on the kind of biomass in question.

Compared to recycling of revenues in a standard fashion, where total CO_2 tax revenues are recycled through the lowering of corporate taxes the method of subsidies in the energy supply sector implies a reduced impact on the economy as price effects on the international competitive position are much lower.

The conclusion regarding recycling and subsidies is dependent on the composition of the energy supply sector and fuel technology in the sector. In the Danish case the substitution possibilities are high today and will probably increase if new capacity will be mainly multi-fuel based. The Danish fuel mix of today with electricity production more than 90% based on coal, leaves very high technical potentials for substitution towards less CO_2 -intensive fuels, but this is not the general case of power systems throughout the world. Emission reduction from CO_2 taxes and subsidies to biomass will probably be less important in most other countries with the existing composition of electricity and heat producing technologies. However, a change in technology composition with larger substitution options between biomass and CO_2 intensive fuels can result in substantial emission reducing effects from a subsidy based policy. The existence of large biomass resources in some countries probably at lower prices also reduces the necessary subsidy.

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Modelling a sector undergoing structural change: The case of Danish energy supply

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department

Abstract

This paper examines structural change in the power and heat producing sector (energy supply) and its implications for the economy. An integrated approach is used to describe the interactions between this sector and the rest of the economy. Thus, a very detailed model of the sector for Denmark has been linked to a macroeconometric model of the Danish economy. It is argued that analysing sectors that undergo radical changes, for example, the energy supply sector should be undertaken by using a model that describes the technological and organisational changes in production along with implications for the demand of the produced goods.

Environmental priorities and targets for emission reductions are important for defining energy policy in Denmark. As the energy supply sector at present is a major contributor to emissions of CO_2 *and* SO_2*, knowledge of this sector is vital for reducing these emissions. It is shown that quite substantial emission reductions are possible without encountering a substantial negative impact on the economy. The reduction potential through such economic incentives as fuel taxes is shown to be very sensitive to the technology used at present and in the future.*

This study also emphasises that the large reduction potential of emissions from the energy supply sector is a one-time gain. Fuel switching and increasing use of wind power cannot be repeated. Scenarios carried out with the combined model show that emission reduction in the energy supply sector will decrease the share of this sector in total emissions remarkably, and that the importance of the sector as a key element in any overall emission reduction strategy will decline.

1. Introduction

For economies in transition, modelling the economy and transition process together is an important but difficult task. Economic models will have to be based on historical observations of which at least some parts are either unreliable or refer to a period of a totally different economic regime. This problem emphasises the question of how to incorporate the structural change of the economy in the economic model. The study reported here illustrates how the transition of the energy supply sector can be modelled and integrated with an economic model of Denmark as well as which consequences this integrated model has for analyses of energy issues.

The energy sector is an example of one in transition both in the case of the transition economies and in many western countries. The sector has been highly regulated in many countries, but changes directed at increasing competition and improving efficiency are taking place globally including economies in transition. Privatisation and regulation of the sector is an important issue in the transition economies. This is partly due to the value of the capital equipment, which consists of long-term network facilities and power plants. Privatising the energy sector is supposed to yield considerable revenues to the public sector, but the possible success of privatisation and the privatisation revenue depends much on the regulatory regime that is introduced in the sector (Newbery, 1994). This is another argument for the relevance of modelling the energy supply sector and the regulation options, including the interaction of the sector with the rest of the economy.

In the first years of transition, energy demand in transition economies will stagnate or decline as a consequence of a fall in industrial production and as prices are adjusted to real production cost probably a rise in consumer prices of energy. In the long term an increase in energy demand must be expected as a consequence of rising growth rates and changes in the composition of household consumption. Efficiency improvements and a decreasing weight of heavy industries will probably moderate the growth of energy demand. Anyhow, in the long run rising energy demand and corresponding increases in emissions related to energy use must be expected.

In many countries including those with transition economies the energy supply sector is a very important contributor to energy-related emissions and vital to any initiatives to reduce these emissions. Regulation and economic incentives in this sector enable emissions from the sector to be reduced considerably. At the same time, for economies in transition in many cases the sector has been subsidised, which has resulted in a lack of economic incentives to improve efficiency in both the production and consumption parts of the energy system.

This study examines structural changes in the Danish energy supply sector, which could be a result of direct public regulation or other energy policies. Empirical models used for policy analyses of economies or sectors in transition must include a description of the structural change and the impact on economic parameters as price elasticities. The model described and used in this paper is an example of an integrated model that can be used for analysing energy policy as well as the impact on energy demand and emissions as a consequence of changes in economic variables. This model and the scenarios carried out show that it is possible to include a transition for a single sector in an empirical model and also that it is important to include the transition effects on parameters when using the model for analysing different economic policies. Tax-based policies to reduce emissions depend on the structure of the energy supply sector, and the change in the effectiveness of a CO_2 tax will be examined here.

Structural change in energy supply is closely related to the fuel substitution options in the sector. In a CGE model study of the Danish economy (Frandsen et. al., 1994) the energy supply sector is modelled with substitution between aggregates of energy, capital and labour but without substitution between fuels. In the power sector substitution between fuels is recognised to be relevant for coal, natural gas and fuel oil, but this substitution possibility is not included in the model, as this would require modelling of the relevant trigger prices. The bottom-up characterised energy supply model used here includes a detailed description of technical parameters that endogenously determine the trigger price for individual production units and the corresponding substitution between fuels.

Substitution possibilities are present in the existing Danish capacity mainly in the form of switching between coal and fuel oil and to some extent natural gas. The scenarios and their results referred in this study assume that future production capacity expansion is dominated by multi-fuel combined heat and power plants. In each new plant this implies the possibility of substituting between using up to 50% biomass or almost 100% coal or fuel oil.

Model results for the Danish case show how a substantial regulating effort in the energy supply sector will decrease emissions. In the long run emissions from the energy supply sector will be of reduced importance and emissions related to end use of fuels will contribute to growing emissions. As the change in economic structure continues, a greater share of energy demand is related to individuals and centrally planned regulation will be of diminished importance in reducing emissions. Thus, focus must shift towards regulation of individual energy demand or introduction of economic incentives for individuals, corporations and institutions.

The model used here is a result of a project about integrating macroeconomic and technical-economic models. A number of technical and microeconomic-based modules for energy demand and supply have been developed. These modules have been connected to the most commonly used macroeconomic model for Denmark. This combined model is called Hybris (Jacobsen et. al., 1996).

This paper is divided into two parts: The first describes the different approaches to energy-economy modelling, the integration of the approaches in the Danish model Hybris and the relevance for modelling economies or sectors in transition. In the second part of the paper Hybris is used to illustrate the importance of modelling the sector undergoing structural changes. Two scenarios, a regulation scenario and a CO_2 tax scenario illustrate the importance of structural change in one sector for overall emission effects of different policies.

2. Modelling structural change in the energy supply sector

The energy supply sector (power and heat) is an important sector for analysis of environmental issues related to energy use. Relevant analysis must include options that will change the structure of the energy supply sector considerably. Modelling this sector implies choosing among different modelling approaches. Energy-economy modelling has been dominated by two different approaches: top-down modelling based on macroeconomic modelling principles and techniques, and bottom-up modelling based on disaggregation and the inclusion of a large number of technical parameters. The different approaches have led to very different properties and model results that have been most widely noticed in the analyses of emissions and mitigation costs. Both older (Hoffman and Jorgenson, 1977) and more recent studies have argued the need to integrate the approaches as they in many cases are of a more complementary than substituting nature.

Technological models have been widely used within energy analysis and planning. Models of this type have considerable detail and describe a number of different energy technologies with both technical and economic parameters. Both present and future technologies are often included, which means that these models describe the change in parameters as fuel substitution options based on knowledge of the stage of development of new technologies. Technological energy models hereby describe a transition process that changes the parameters of behavioural relations such as fuel price elasticities. Models can be both optimisation or simulation models and are often referred to as bottom-up models.

Energy-demand relations for technological models of the energy supply sector could be specified as

$$E = \sum_{i=1}^{n} \frac{\left(P_i + Q_i\right)}{\eta_i(f_i)} t_i \qquad (1)$$

P_i Electricity production at plant i
Q_i Heat production at plant i
f_i Fuel mix at plant i
η_i Fuel efficiency at plant i, dependent on fuel mix
t Plant operates or does not as the shutdown time is known
D Demand for electricity and heat

$P_i + Q_i$ is found by specifying full load hours for each plant exogenously or by the production that results from sorting the plants by the marginal production cost of electricity and setting their production according to their position along the duration curve until the plants necessary to meet the total electricity demand are put into operation.

Macroeconometric models are characterised by estimated behavioural relations at an aggregated level. Models developed specifically for analysing energy issues as well as models of a more general macroeconomic type are used. The models are based on different economic traditions and both neo-classical and Keynesian-based models exist. Also, there is a difference in the time spans covered by the models. These types are referred to as top-down models.

Top-down specifications of energy demand for the energy supply sector could be

$$E = e(p_i, p_j, aeei, D) \qquad (2)$$

p_i Price of different fuels
p_j Price of other production inputs
$aeei$ Autonomous energy efficiency improvement (indexed conversion efficiency)
D Demand for electricity and heat

The different approaches reflected in the specifications of energy demand above are a consequence of different theoretical backgrounds and modelling practices. In some respects the technological and the macroeconometric approach are complementary. The autonomous energy efficiency improvement is exogenous to the macroeconometric model. In the technological model the vintage effect through technology improvement connected to the replacement and expansion of existing production capacity could give a better description of fuel efficiency developments.

With regard to the effect of fuel price changes, the two approaches are fundamentally different. The macroeconometric approach is based on an estimation of historical relations between fuel prices and fuel demand and assumes that the behaviour reflected in the estimated elasticities is constant. Technological models describe the development in the fuel technology used and indirectly how options for fuel substitution change with time. This means that elasticities will also change with time and possibly even that fuel demand changes only when certain levels of relative fuel prices are reached. In some instances technological models do not include any response to fuel price changes at all.

For the energy supply sector the macroeconometric approach leads to practical problems when estimating fuel price elasticities. The estimation requires that a time series of fuel prices and fuel consumption be given. This empirical material is not always at hand. When natural gas is introduced for use in the energy supply sector, empirical data for estimating elasticities between natural gas and other fuels are absent and the share of natural gas of all fuels will have to be put as an exogenous variable in the macroeconometric model. At the same time the energy supply sector is often a regulated one. This means that the very long-term decisions about fuel technology and fuel use are influenced not only by fuel prices but also by political opinions. Therefore empirical estimates of parameters in macroeconometric models of the energy supply sector tend to be unreliable and insignificant. I will refer to this as the parameter problem for macroeconometric models of the energy supply sector.

The energy supply sector is an obvious sector to describe with a technological model without constant fuel price elasticities. At the same time it is relevant to include some fuel demand responses to fuel price changes. Short-term responses (within a year) will depend on the technology used in the production capacity at the time of price change, which could very well be described in a technological model that includes cost minimisation. Long-term fuel price effects depend on both the organisational structure of the energy supply sector and vintage effects of existing capacity. Direct regulation of the sector could be the driving force for long-term fuel changes, but if the sector is moving towards deregulation the fuel price becomes a more important parameter for long-term fuel demand changes. Long-term fuel price effects in the energy supply sector can be found in the optimisation models MARKAL and EFOM.

A combined model that integrates the two approaches with both fuel price effects in a technical model of the energy supply sector and with linkages of the energy supply sector to the rest of the economy gives a better description of energy issues, policies and their consequences for the overall economy. Thus, such a model will be able to analyse more complex issues incorporating both regulation of the energy sector and energy tax policies including the interdependencies between the energy system and the economy.

Some studies have worked along this idea and integrated the approaches by linking technological and macroeconometric models. One of the most widely used models resulting from this linkage is MARKAL-MACRO (Manne and Wene, 1992), which integrates a technological optimisation energy model MARKAL; that have been used for several years, with a specially designed MACRO model. Other integrated approaches for the energy supply sector include GLOBAL 2100 (Manne and Richels, 1992), which in a long-term growth model incorporates an optimisation between energy technologies, which is to be made available at some time in the future.

The model for Denmark described below lies within this integration approach. A main difference between the model used in this analysis and MARKAL-MACRO is that the macroeconomic part of our model is an econometric simulation model of Keynesian origin. Thus, there is no objective function in the underlying macroeconomic part of our model. MARKAL-MACRO on the other hand includes a long-term neoclassical growth model MACRO, which includes an objective function that maximises consumption representing utility. MACRO has an economy-wide production function with inputs of capital, labour and energy. Energy is treated as useful energy services delivered by MARKAL.

3. Model description

Hybris is a linked model based on three technical energy modules and a macroeconometric model for Denmark. The three energy modules describe the energy supply sector, household demand for heating and household electricity demand. These modules have been connected to the most commonly used macroeconomic model for Denmark called ADAM[1]. In this paper only the energy supply module and the links to ADAM are described.

Hybris takes explicitly into account the interactions between the energy system and the economy. The links from regulation of the energy supply sector to the prices of electricity and heat, and the resulting demand response from households and firms are modelled. Economic incentives through energy taxes are included and links to the energy supply sector are described. The important links between the energy supply sector and the macroeconomic level of the model are illustrated in Figure 1.

Basically ADAM is a demand-determined model with a detailed input-output structure. In ADAM energy demand for households is determined depending on energy price and income. Industrial energy demand is determined by the energy price, the value added and an exogenous trend in the energy efficiency. The economy is divided into 19 industries and for each of these, energy demand relations are estimated. Private consumption consists of 8 consumption groups of which two have a substantial energy content. ADAM is a short- to medium-term model.

The original energy supply sector of ADAM is very simple. There is no description of fuel substitution and no representation of technologies as wind power or combined heat and power. For any analysis of energy-related emissions this modelling of the energy supply sector is not satisfactory. Thus, in the Hybris model we have included a very detailed modelling and description of the energy supply sector.

The macroeconomic consequences, which are included in the scenarios described later, depend on the characteristics of the macroeconomic model ADAM.

The module covering the energy supply sector is characterised as a bottom-up module. It includes a very detailed description of the major power plants in Denmark with technical parameters as energy conversion efficiency, fuel substitution limits on individual plants, plant capacity, lifetime and co-generation parameters. In the model economic elements represented by prices and cost minimisation are also very important in determining fuel demand.

[1] Annual Danish Aggregated Model.(For a documentation see Danmarks Statistik, 1996.)

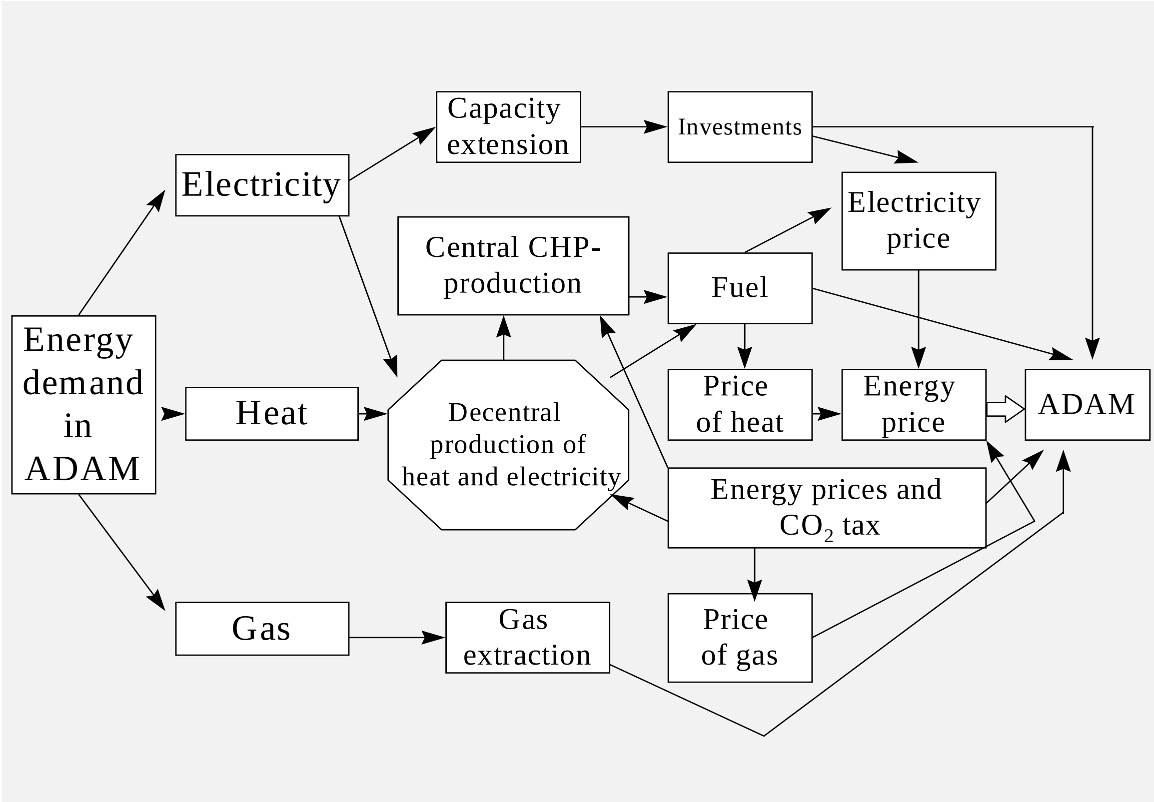

Figure 1 Links between the energy supply sector and the economy in the Hybris model.

The energy supply module is in itself an example of the integration of bottom-up and top-down approaches to energy modelling. Unlike most bottom-up studies that do not include price-induced feedback effects on energy demand (Chandler, 1994), the model used here through the link to a macroeconomic model and an iterative procedure takes explicit account of the interaction with the economy.

Fuel input in electricity and heat production is given by minimising total fuel cost for electricity and heat generation by the 50 major power plants of Denmark, which are primarily combined heat and power plants. In minimising production cost substitution between fuels is allowed within the technical constraints specified for each plant. Fuel demand from each plant is found based on a duration curve for electricity demand. This duration curve is based on the assumption of 365 identical 24-hour periods, and the use of a linear approximation. Heat is assumed to be storable to the extent necessary within the 24-hour period and no duration curve is applied here.

Given the cost minimising fuel mix on each plant they are sorted according to marginal costs. Thus substitution between plants with differing production costs takes place within the bounds given by the duration curve. Plants with high marginal costs (fuel costs) will have short producing times, but as long as the peak demand includes the capacity they will produce.

As the production frontier of each plant is constrained by linear restrictions the calculations for the centrally planned operation of large power plants in Denmark is characterised as a linear optimisation problem. The dual problem to the minimisation problem of fuel costs is maximising revenues, which is done at the decentral level. For each plant the production is found by maximising the revenue based on shadow prices for heat and power. By running two iteration procedures the required electricity and heat production is distributed on individual plants. First, electricity production is distributed according to the marginal production cost given the shadow price of heat. At the upper iteration level the shadow price of heat is adjusted to reach the required heat production. In this way, the combined production cost of heat and power is minimised for the large power plants.

An exogenous fuel demand is given from secondary power and heat units with an exogenous capacity and exogenous number of full load hours. The expansion technology for the new plants is handled exogenously, but technical parameters change over time and the endogenous expansion of production capacity in large units acquires the technical parameters determined by the year they are built.

A detailed description of electricity price formation is included following the official restrictions given by Danish legislation. In principle, prices are given by average cost as the utilities are not allowed to generate any surplus. The interesting and fluctuating parts of the cost determination for electricity prices are fuel cost and especially allowances on capacity under construction. The total investment cost of large power plants can be written off in only 5 years during their construction, where the physical lifetime tends to be 25-30 years. By this legislation Danish consumers directly and immediately pay for new plant construction.

Investments in electricity production capacity are calculated from the expansion of capacity and are linked to the investments of the energy supply sector in ADAM.

The most important properties of Hybris originating from the integration of top-down and bottom-up approaches include:

- The effect on electricity prices and electricity demand as a consequence of regulating fuel mix and capacity expansion technologies in the energy supply sector affects the energy demand in top-down relations in ADAM.
- Changing macroeconomic conditions affect the energy system structure and feed back to the economy through changing energy prices and investments.
- Energy price elasticities are low (-0.2) in the macroeconomic relations for industrial energy demand, very low (-0.1) in household energy demand but at the critical levels for relative fuel prices very high for the energy supply sector.
- Macroeconomic costs of emission reduction initiatives arise through price effects. In the Hybris model the macroeconomic cost of reduction initiatives seems moderate (around 1% of GDP) for a CO_2 tax of 50 USD/ton of CO_2.

Fuel price effects are more important in Hybris than in both the macroeconomic model ADAM itself and particularly in traditional bottom-up models, where price effects are almost non-existent. The increased price effect originates from the high degree of fuel substitutability in the energy supply module and is primarily connected to the choice of fuel input in electricity generation. The fuel price elasticity in this module is far from constant as is often the case in macroeconomic models. It is very hard to find econometrically reliable relations for fuel demands in the energy supply sector, which sometimes forces macroeconomic models to exempt fuel substitution in the sector by distributing total fuel demand on fuel types by coefficients.

4. Emission reduction and regulation of the energy supply sector

The energy supply sector is a main contributor to emissions in Denmark. In 1991 as much as 52% of CO_2 emissions and 74% of SO_2 emissions can be attributed to energy conversion. This means that the energy supply sector is in focus when emission reduction policies are examined. Relatively small gains in the sector will have a high impact on the aggregated emission figures.

In a regulated market, such as occurs in the sector of electricity and heat production in Denmark and without knowledge of fuel demand parameters from electricity and heat producers, regulation of fuel mix and technology of new production capacity is the obvious way to reduce emissions. It is relatively easy to design a policy to reach some target of emission reduction within the sector if the future demand development is known. What is not obvious is the response from consumers of electricity and heat to price changes induced by the regulation.

In Hybris the energy supply sector represented by electricity and heat production is modelled in detail and therefore both incentives through economic measures as CO_2 taxes as well as regulation of fuel mix in new plant capacity can be analysed. It is possible to compare the effects of technology regulation and regulation through CO_2 taxes on fuels. Regulation of the technology that will be used in future expansion or replacement of power and heat capacity has an influence on the effect of CO_2 taxes. With Hybris the interaction of the tax policy and the direct regulation can be analysed.

The sector can be regulated by adjusting the fuel mix of new plants, all of which have to be approved by the authorities. In this way future options for changing fuels can be ensured and the energy conversion can at any time take place with minimum fuel cost. Alternatively, the fuel used in the sector could be regulated either by shares of different fuels or by some absolute volume used. This is relatively unproblematic if the system is centrally planned as in the Danish case today, but if the power and heat production have been deregulated and split into several independent producing entities, this kind of regulation probably will not result in an effective production structure.

The transition to freer and more price-based market economies leads to an increased use of economic incentives in policy making. The lack of experience with price reactions from consumers is essential in building an economic model of the kind used here, also when choosing the appropriate policy to reach targets in an overall policy. Parameters describing economic behaviour will either be estimated very inaccurately or their values might be taken from other sources.

A model that comprises both planning, regulation and economic behaviour is essential when analysing economies or sectors that are partly regulated and are undergoing structural change. The parameter inaccuracy problem will be of reduced importance in such a model relative to pure econometric models.

The Hybris kind of model is capable of illustrating the energy- and emission-relevant part of an economy in transition from a highly regulated to a deregulated market. However, the macroeconometric part of the model described here is not a relevant tool for analysing economic issues of economies in transition. The ADAM model is an econometric model for a market-oriented economy such as the Danish.

5. Changing the structure of the energy supply sector by regulating the technology used in new capacity

A policy directed at introducing more renewable energy in the production of electricity and heat is evaluated with Hybris. The policy mix called the regulation scenario consists of the following elements:

- Expanding wind energy capacity by 100 MW a year until 2005 and 50 MW a year from 2006 and forward. This is compared to a base case with 50 MW and 25 MW respectively.
- All new large power plants are forced to use 50% biomass in their fuel mix.
- Large power plants that have technical options for using natural gas must do so.
- New decentral combined heat and power plants must use biomass.
- From 2005 heat production is nearly fully based on combined heat and power.

This policy changes the production structure in the sector. Figure 2 shows the shares of electricity production by different production categories. By 2020 more than 40% of the electricity production is based on wind energy and decentral heat and power compared to around 15 % in the present Danish case.

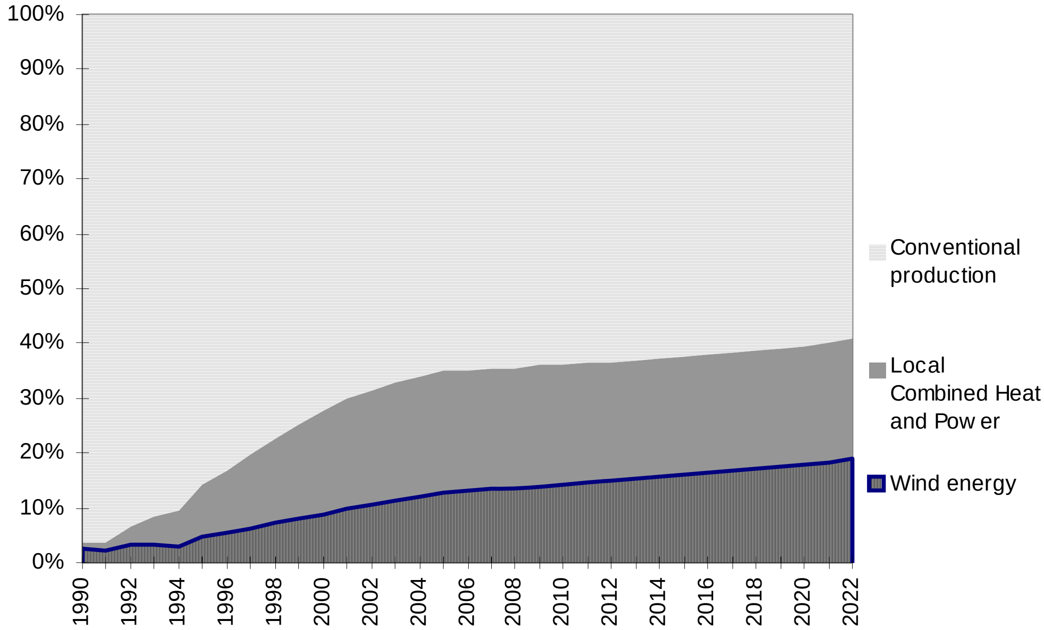

Figure 2 Power produced by different production categories

The most important links from structural change in the energy supply sector to the economy go through the prices of electricity and heat. Compared to the base case the price of electricity is rising. As wind energy capacity is expanded the capital costs of the total electricity production and distribution is increased, but some years later the planned expansion with a new power plant can be postponed and the capital cost are accordingly shifted to a later period. This is what is observed in Figure 3 where around the year 2008 prices in this scenario are lower than in the base case. The expanded wind capacity offsets some traditional capacity expansion, which due to the discrete nature of capacity expansion (in our case by plants with the size of 400 MW) results in lower prices in a few years and higher electricity prices in the rest of the period.

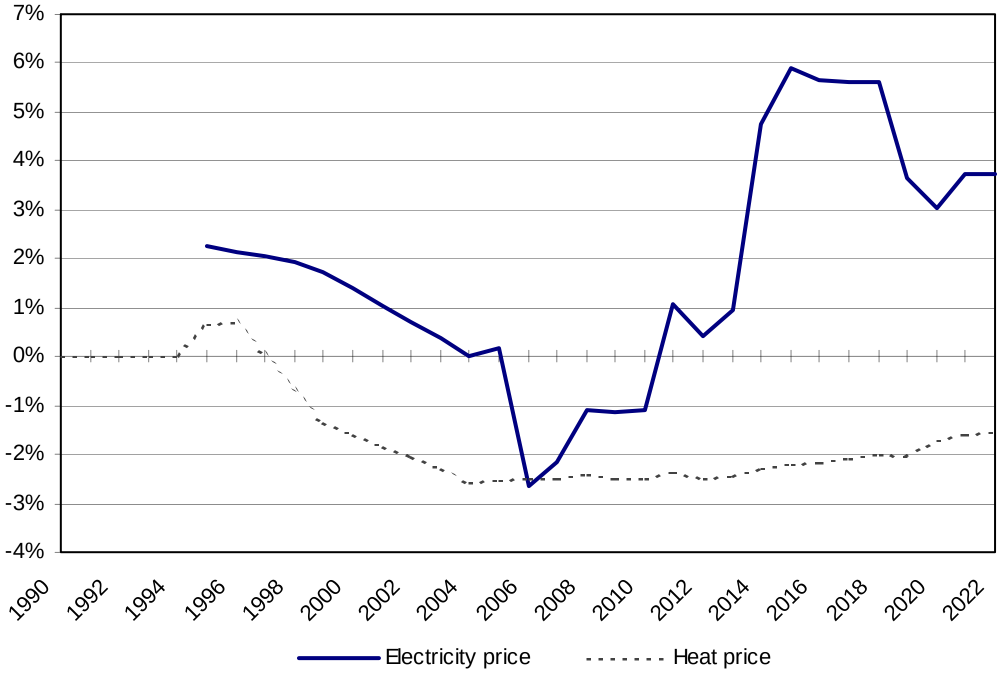

Figure 3. The change in prices connected to a change in the structure of the energy supply sector

The change in the production price of electricity and heat results in a demand response from households and industries. The demand response from households is rather low as the consumption price for households includes more than 60% taxes. In the model the consumer price of energy is an aggregate of all energy inputs in household heating and electricity consumption. The consumer price of energy inputs rises around ½% compared to the long-term rise in electricity production price of around 4% (see Figure 3).

With energy price elasticities of around -0.2 the demand response to this structural change is very small. But the structural change has other effects on the economy. Because of the uncertainty in wind production availability the expansion of the wind energy capacity only partly replaces other expansion of capacity. In the model this is expressed by a low capacity value for wind (25%), which means that the necessary expansion by traditional central power plants is only reduced by 25% of the expansion of wind capacity. Investments in the energy supply sector will rise and this has positive implications in a demand-driven model like ADAM.

Another impact on the economy is established as the increased biomass demand is directed towards agriculture, where biomass is considered a by-product (straw) thereby increasing the income of this sector.

Finally, the increased biomass use offsets the use of coal, which has a positive effect on the current account. Consequences on GDP, investments and private consumption are shown in Figure 4.

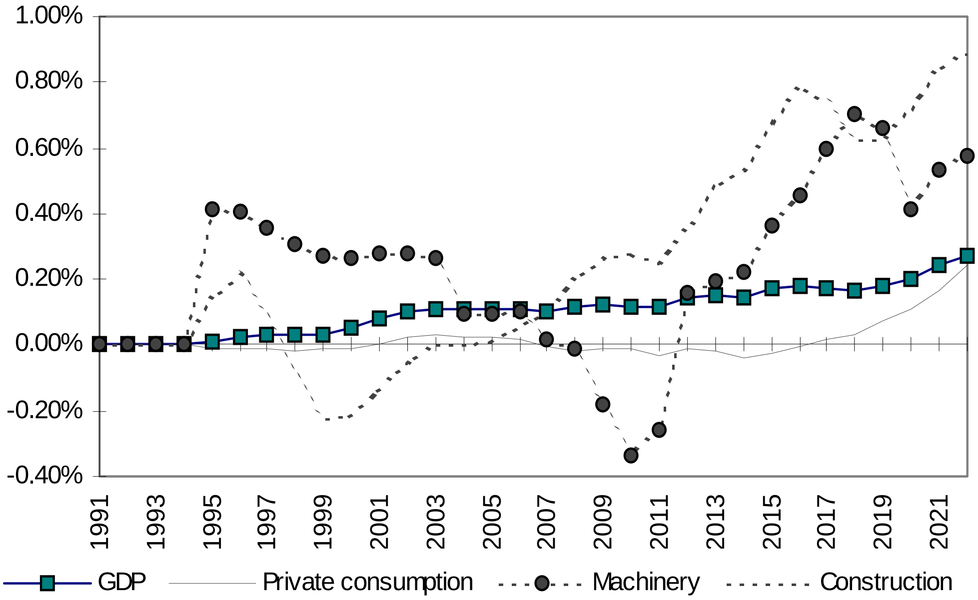

Figure 4 Real effects of the regulation scenario relative to reference case

The economic consequences for the economy of a regulation policy are relatively small. In contrast, the effects on emissions are large both for the emissions from the energy supply sector and for reduction of emissions for the overall economy.

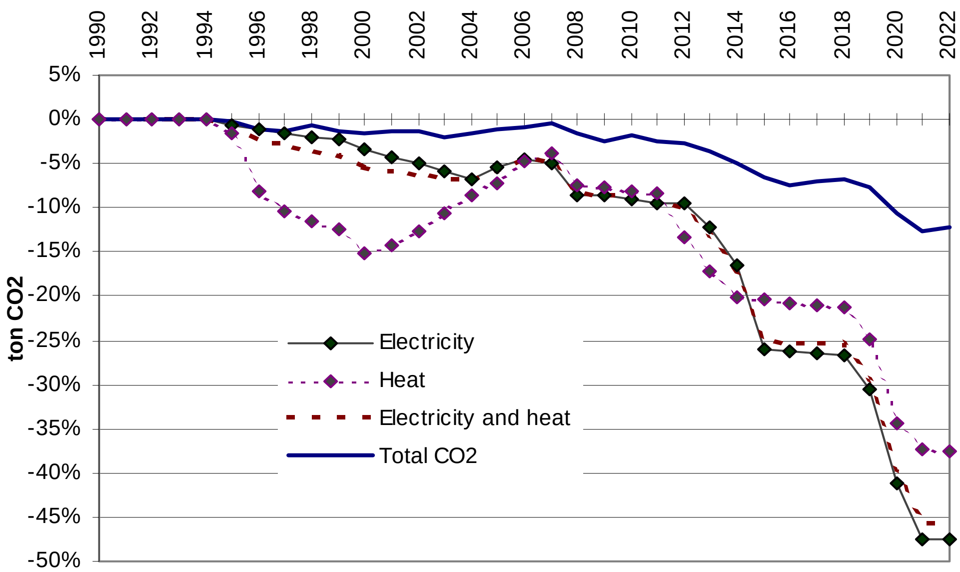

Figure 5 Emission of CO_2 in a regulation scenario compared to the reference case

In the long run emissions from the energy supply sector are reduced by 50% and for the economy this leads to an annual reduction of CO_2 emissions of 12%. From 2012 the reduction is achieved mainly as a consequence of replacement of old coal-fired plants by new multi-fuel plants, that use 50% biomass. The long-term reduction could be achieved faster if coal plants are replaced before they are physically worn out.

If the policy and the technical options for regulating the energy supply sector are implemented to the extent assumed in the regulation scenario, further reduction initiatives will have to be directed towards end use of energy, both at consumer and industrial levels. In Figure 6 the regulations on the Danish power and heat supply sector described above are included. In 30 years the energy supply sector will be responsible for less than half the share of emissions it is today. Further regulation of this sector will in this long perspective have a limited influence on the overall CO_2 emission for the Danish society.

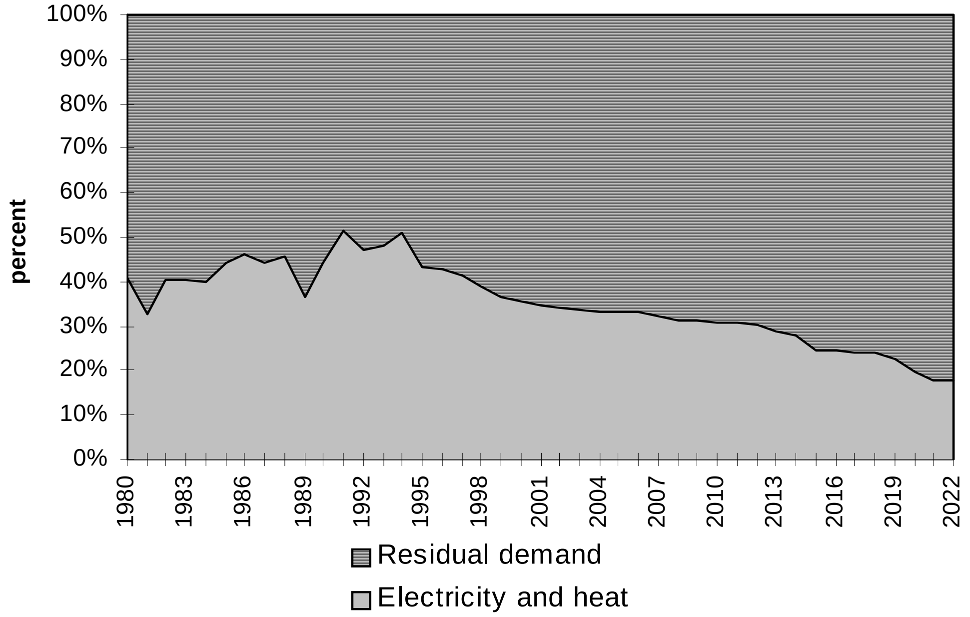

Figure 6 Share of total CO_2 emissions

Structural change induced by an emission-reducing policy change the effect of further policy initiatives in energy supply, and as a consequence policy focus has to change to other parts of the energy system.

6. Transition in the energy supply sector changes the emission reducing effect of CO2 taxes

A CO_2 tax could be implemented as an alternative to the regulation policy to reduce emissions. This more market-oriented instrument could prove more cost-effective if the structure of the energy supply sector were more fragmented with respect to ownership.

In the Hybris model developments in fuel substitution possibilities due to change in technology are included. The technical constraints in the energy supply system are very important when analysing the effect of a CO_2 tax. The long-term nature of the power and heat capital is reflected in a physical lifetime of around 30 years. In combination with the stagnating power and heat demand in Denmark this implies that more flexible multi-fuel plants will be introduced only if fuel prices are rising substantially or as old production capacity is replaced. In this case the effect of moderate CO_2 taxes will be relatively low initially and will increase, as a higher share of production capacity will acquire technically fuel substitution options. The transition of the capacity to more flexible multi-fuel plants, as in the Danish case, illustrates a move towards greater influence from fuel tax policies.

The emission effect of a CO_2 tax of 50 USD per tonne of CO_2 imposed on all fuels used in the Danish economy is shown in Figure 7. Tax revenues are recycled to industries by lowering the corporate income tax rate.

Until 2005 the emission reduction in the energy supply sector is seen to be moderate. But gradually as new plants are built with a 50% share biomass option the emission effect compared to the base case is increased. In 30 years time most of the production capacity includes a biomass option and the effect of the tax is a 50% reduction of CO_2 emission from the energy supply sector. Total CO_2 emission of the Danish economy is reduced by 15%.

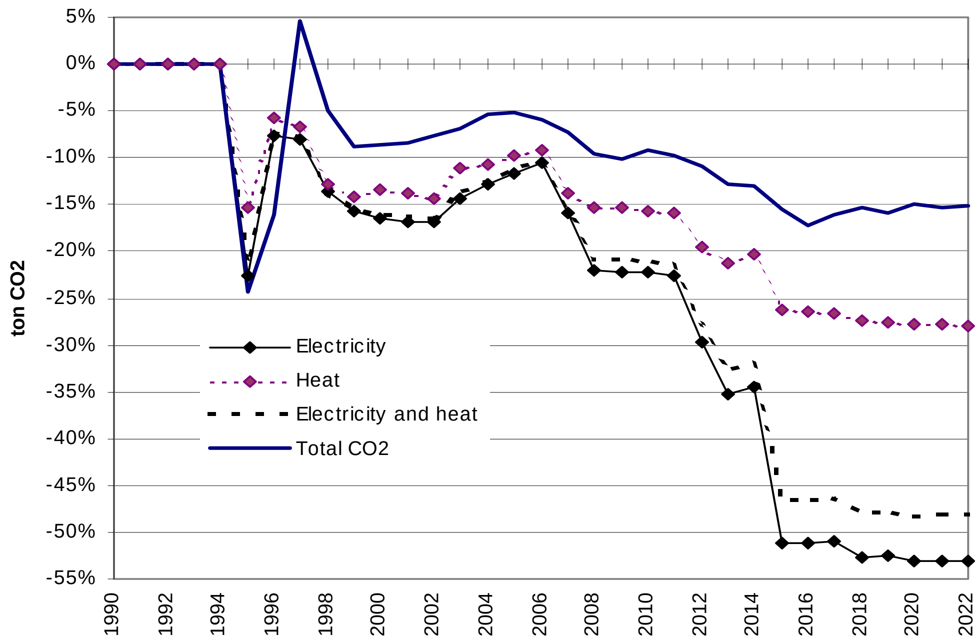

Figure 7 Reduction of CO_2 emission as a result of introducing a CO_2 tax on fuel input in the energy supply sector.

The results above indicate that in the centrally planned energy supply sector[2], similar emission reductions may be achieved with direct regulation of fuel use or fuel taxes. This result holds only if the technology in new plants is regulated to include the biomass option as is assumed here.

Price effects on electricity demand from households and industry are included in both scenarios analysed, but in the regulation scenario the price effect has only limited effect on electricity and heat demand. The price effect of a CO_2 tax is higher because the tax is imposed on all energy use in the economy and also because the tax raises electricity and heat production cost more than the extra investment cost from the regulation scenario.

[2] Denmark has a long tradition for regulating public utilities

Thus, the emission reduction in the overall economy will be larger with a CO_2 tax than that which is induced by a direct regulation. The larger emission reduction corresponds to the macroeconomic cost of a CO_2 tax that arises through higher energy prices, labour cost and decreased competitiveness. Macroeconomic consequences of a CO_2 tax are illustrated in Figure 8.

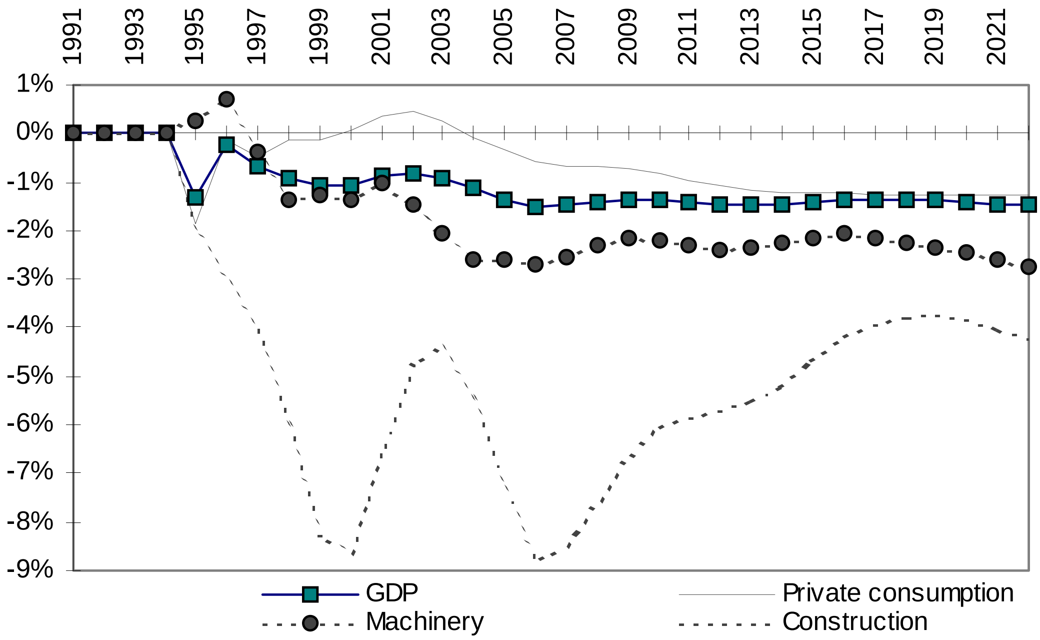

Figure 8 Macroeconomic consequences of a CO_2 tax of 50 USD per tonne CO_2

Compared to the reference case the level of GDP is reduced by 1% in the tax scenario. Construction activity experiences a large drop, which is mainly a result of the delay and the reduced need for the construction of new heat and power plants. Machinery investments are decreased as well, but the share of the energy supply sector in total investments in machinery is relatively small. Private consumption is reduced only in the long run, when the negative impact of energy and labour cost on the competitive position results in a reduction of production and employment.

As in the regulation scenario agricultural production has been increased in the tax scenario, and because the same plants change from 100% coal fired towards 50% coal and 50% biomass the effect is of similar size. The only difference is that electricity demand is reduced more in the tax scenario and this implies a lower power capacity. The total new capacity with biomass option built in the period has been reduced by 800MW equal to two multi-fuel plants.

The scenarios described above show that a policy to combine economic incentives to ensure cost-effectiveness in the short run and planning to ensure fulfilment of the long term environmental targets could be designed and analysed in the kind of model used here.

If the energy supply sector is undergoing a transition towards freer markets and an increasing number of independent production units, a regulation of the fuels used on each production unit will not be effective or possible. Alternatively, a combination of regulation of the technology and taxes on fuels could be used to achieve the same reduction as could be accomplished with direct regulation and a centrally planned energy supply sector.

7. Concluding remarks

This paper has emphasised the importance of addressing the energy supply sector not only by macroeconometric modelling but also by modelling the technical constraints and regulated elements of the sector that produces electricity and heat. The energy sector is an example of a sector in transition. Both the technical equipment with important characteristics such as fuel substitution options and the organisation of the industry are undergoing radical changes in many countries including those with transition economies.

Transition of the energy sector cannot be described in a macroeconometrically based model because the historical behaviour reflected in the estimated parameters depends on both the technology used in the past and the organisational structure of the sector. A combined model describing the transition of the energy sector in detail and the important links to the economy is more appropriate. Such a model was used here, and in two different scenarios it has been shown that results from analyses of emission-reduction policies depend very much on the options for fuel substitution described in the detailed technical model.

A scenario describing a policy of increased use of renewable energy, led to a reduction of CO_2 emission without a negative impact on the economy. However, the reduction was achieved by changing the technology used in electricity and heat production and this changed the characteristics of the sector including future fuel substitution options. If a drastic change of the energy supply sector were to take place the emission share from the sector would decline and policy effects from initiatives in the sector would be of reduced importance.

The second scenario showed the importance of including technical parameters when analysing economic instruments as a CO_2 tax. The effect of a CO_2 tax on the fuels used in the energy supply sector is very dependent on the technical fuel substitution possibilities which are related to the long-term expansion and replacement of production capacity in the sector. In the scenario with a CO_2 tax it was shown that an emission reduction equal to that in the regulation scenario could be achieved without much negative impact on the economy.

The model described in this paper gives the possibility to compare different policy strategies of regulation and tax incentives when a sector such as the energy supply sector is undergoing radical changes.

Acknowledgements

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Energy technology and foreign trade: The case of Denmark*

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department, PO Box 49, DK 4000 Roskilde,
henrik.jacobsen@risoe.dk

Abstract

This paper address two issues related to energy technology and trade. First it examines the importance of changes in energy technology for long-term trade developments of the Danish manufacturing industry. Secondly the trade potential of a policy to support the development of environmental friendly energy technologies is examined.

Energy technologies affect the competitive position of industries through their energy costs. This paper presents an empirical investigation of the Danish industries with respect to the energy intensity and the relative production development of the energy intense industries relative to the average industry.

Another important effect of the change in energy technologies is the competitive option for the industries producing the capital equipment of a specific energy technology. Here the consequences for the Danish wind turbine manufactures and for the manufactures of pipes for district heating can be highlighted. Exports of the environmental friendly technologies are found to be the most important contribution to trade figures in the Danish case.

1. Introduction

Energy demand changes that are related to change in trade patterns have implications for different issues as energy efficiency developments for industries, international comparisons of energy demand and the discussion of the relevance of different policy measures to reduce greenhouse gases.

Changes in energy technology have impacts on foreign trade through different channels. Three different aspects of change in technology can be highlighted.

- Change in energy efficiency and technology has consequences for the competitive position of industries.
- New energy technologies creates export possibilities.
- Energy technology change and trade in energy commodities.

Denmark has very few energy intensive industries today. To some extent the development of energy technologies and energy policies for the implementation of new technologies have contributed to less energy intense industries in Denmark. It also seems that the relatively energy intensive industries have succeeded in energy efficiency

* Forthcoming in ***Energy and Environment*** 11 (1)

improvements to some extent accomplished by changing their activities towards more R&D and consulting. Any expansion of the energy intense part of production have then been placed abroad. There are several other explanations of why the share of energy intense industries of Denmark have decreased. Energy intense industries will, for example, often be characterised by increasing returns to scale. With high energy cost shares the international competitive position have been dependent on the ability to decrease energy costs and compete or to lose their market.

The relative importance of technological progress in energy technologies versus labour augmenting technological progress is not very clear. For the industries with low energy intensity it is possible that cost reductions to some extent have been achieved by investments aiming at reducing labour input but not reducing energy input. For the energy intensive industries it is possible that some have achieved cost reductions by changing energy technology or introducing conservation technologies. The degree to which this has taken place or if a failure to reduce energy intensity and costs has led to stagnation or decline in these industries will be examined in here.

The availability of cheap power resources of a non-transferable nature and located at remote places has led to a concentration of the very energy intensive industries at such locations. Denmark has no such resources and no new energy intensive industries have been located here.

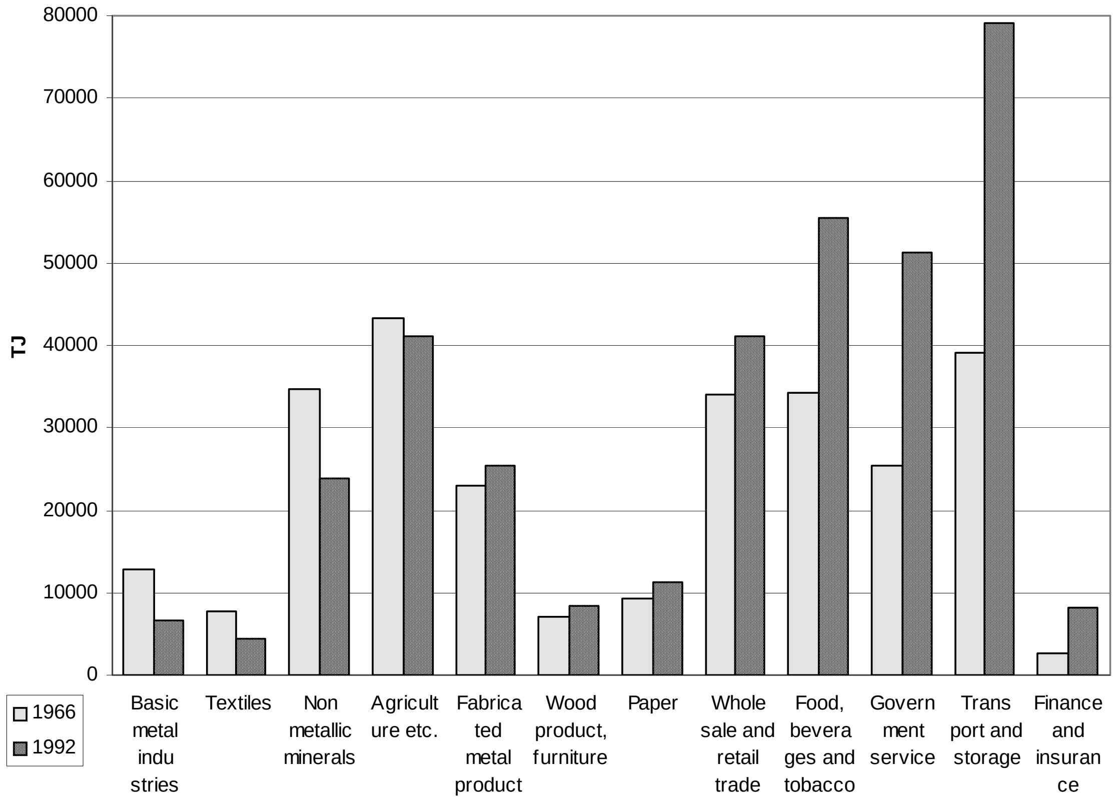


Figure 1 Energy input in Danish industries, 1966 and 1992

The industries in Figure 1 are sorted by the relative change in energy demand from 1966 to 1992. In the service sector energy demand have increased quite substantially, while in some of the manufacturing industries and agriculture energy demand have fallen. Much of the explanation for this development must be that the service sectors share of total production have increased relative to the more primary industries, but there are at the same time changes in the energy intensity in the sectors where especially the manufacturing sectors have experienced a fall in energy intensity.

The change in energy technology and energy conservation technologies has created export opportunities for Danish industries. This has especially been the case for wind turbines and district heating pipelines. With regard to conservation and cleaning technologies both the sector producing insulation materials and also production of de-sulphuring equipment have benefited. Also the service sectors of consulting on energy technology implementation and energy planning have raised considerable export earnings. Some of these export stories will be quantified below.

A very large impact on the balance of trade can be attributed to a change in trade with energy commodities. Much of this change has nothing to do with a change in energy technology, but to the extent that a change in fuels can be characterised as a change in technology especially the introduction of coal for power production and natural gas in particular have had large impacts on the balance of trade. Another issue is the trade in electricity, which is of growing importance with large annual fluctuations and increased transmission capacities. The dominating power production technology today of combined heat and power has also implications for the possibilities of trade in electricity.

2. Production and export performance related to energy intensity and energy technology

In the period from the mid sixties to the early nineties the energy technology used in production sectors as well as in energy conversion has changed drastically. The economy has become less energy intensive due to a change in the composition of final demand and a change in production structure along with a reduction in energy intensity for nearly all sectors. In a study by Pløger (1984) the Danish domestic energy use as well global energy content were examined. The decomposition of global energy consumption for production of Danish final demand shows that the structural components of io-structure and composition of final demand are even less important for change in global energy content than in a decomposition of domestic energy use for production. Another result is that the effect from changes in imports tended to decrease the part of global energy content in final demand actually being used in Denmark. One reason for this last result could be that Danish industries with high energy intensity have behaved relatively worse than the average industry with respect to import competition. The study of Pløger analysed data for the period 1966-1979 were as this study uses data for 1966-1992.

Manufacturing industries are relatively less energy intensive compared to international levels. This is mainly a result of the very few energy intensive industries in Danish manufacturing. An interesting question is the performance of manufacturing industries with respect to production dependent on the energy intensity of their production. It is obvious that manufacturing as a whole have experienced slower demand growth than the overall economy due to a shift in consumption towards services. But it is not necessarily the case that the energy intensive industries should experience slower growth than the energy extensive industries.

Energy intensity classification 1992 TJ/mill DKK	Share of manufacturing production 1992	Average energy intensity TJ/mill. DKK	Change in production 1966-1992	Change in exports 1966-1992	Share of direct exports in production 1992
< 1	86.2%	0.41	+83%	+193%	50%
1 – 3	12.3%	1.67	+62%	+293%	40%
> 3	1.5%	6.71	-1%	+135%	49%
Total manufacturing	100.0%	0.66	+78%	+199%	49%

Table 1 Change in production and exports dependent on energy intensity

In the table 82 branches of manufacturing have been grouped according to their energy intensity in 1992. Especially the four very energy intensive branches: cement, structural clay products, paper and pulp, iron and steel works, have experienced a much less favourable development than the majority of manufacturing industries. Also the group that consist of 18 manufacturing industries with energy intensity between 1 and 3 TJ/mill. DKK have experienced slower growth than the average.

Energy intensity classification 1992 TJ/mill DKK	Share of liquid fuels 1966	Share of liquid fuels 1992	Share of electricity 1966	Share of electricity 1992	Share of natural gas 1992
< 1	52%	18%	33%	64%	6%
1 – 3	68%	27%	18%	42%	14%
> 3	66%	10%	15%	48%	11%
Total manufacturing	55%	19%	30%	61%	7%

Table 2 Fuel technology change

The very energy intensive industries have more substitution possibilities between fuels than the two other groups. This can be seen from Table 2 where the energy intensive industries reduces the share of liquid fuels much more drastically than the two other groups. It is also for the two most energy intensive group of industries that natural gas has been most widely introduced. For the manufacturing industries with low energy intensity the share of electricity is very high. This is a result of a limited number of processes where there are any alternative to electricity. It is only due to the inclusion of iron and steel works that the energy intensive industries have an electricity share of 48%. In iron and steel works the electricity share is as high as 83%.

Fuel technology change is closely related to emissions form Danish production activities. Wier (1998) in a decomposition analysis shows that one of the major explanations for change in emissions from Danish production 1966-1988 is the change in fuel mix.

Energy technology change can to some extent be represented by the change in fuel use. The general pattern for manufacturing is a reduction of liquid fuels and an increase in the share of electricity. The decline in the use of liquid fuels is general with one exception (book printing) also if all 82 branches of manufacturing is examined (Appendix A). This indicates that the reduction in energy intensity been partly accomplished by reducing the processes using liquid fuels, that means a move towards more sophisticated processing for all the manufacturing industries. To some extent the processes using liquid fuels have changed towards use of natural gas, in some instances coal (sugar factories and refineries), electricity in the case of steel works, and in some cases district heating.

Fuel technology change has been necessary to compete internationally. If the large share of liquid fuels had persisted the production costs would have included a much larger energy dependency. In some cases industries that had less substitution options have been hit by international competition. This has been the case for: structural clay products, paper and pulp, manufacture of raw glass and basic plastic materials. For the last two industries the energy intensity have been reduced drastically which is a result of closing down some very energy intensive plants, and the structure within the industry changing totally towards production of different and new products. For both these industries the product change has been accompanied by success in export markets.

3. Trade patterns, cheap energy and taxation

Denmark has a very energy extensive production structure today. The availability of cheap energy resources at other places has led to stagnation or decline for the very energy intensive industries that existed in Denmark in 1966.

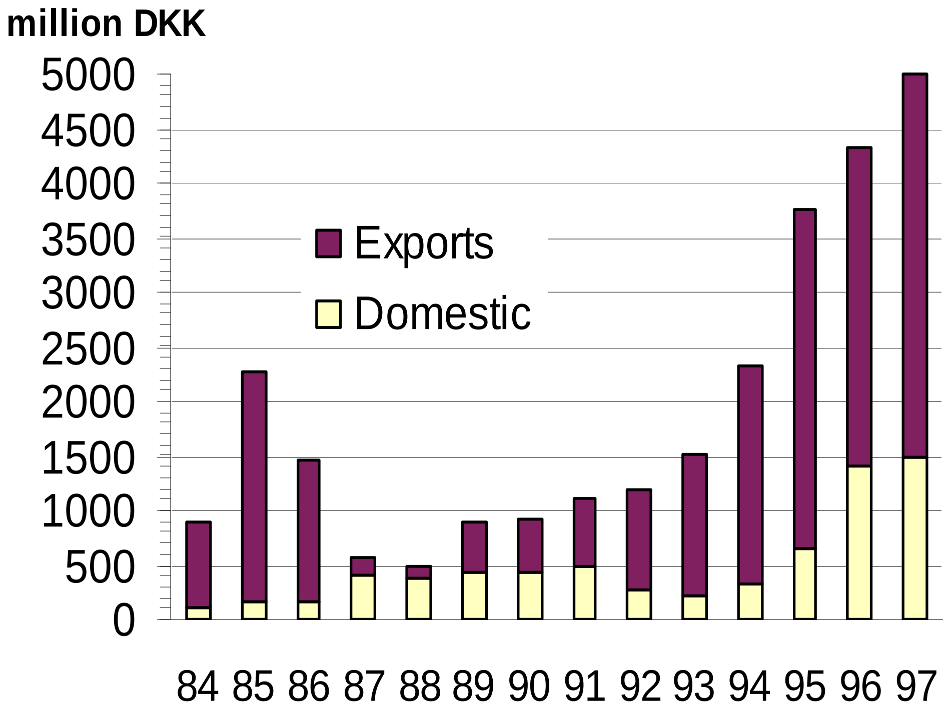
On the other hand the price on energy actually paid by the industries has been relatively competitive to the energy prices paid in other countries. Taxation on energy use has not been widespread and the competition-threatened industries have always been widely exempted from energy taxation. Electricity has been low priced relative to many other European countries. Compared to this the consumer has been very heavily taxed with respect to energy consumption.

The change towards reliance on electricity instead of liquid fuels has not it self contributed to changing trade patterns, but it is an indication that Danish manufacturing has increased labour productivity by increasing electricity based capital equipment. This has contributed to maintaining international competitiveness of Danish manufacturing.

Cheap energy is important when energy is a main input and hereby an important determinant for competitiveness. For the very few energy intensive industries in Denmark there has not been cheap energy available. Cheap energy available can be a result of either a subsidisation of energy or the existence of specific local resources e.g. hydropower or natural gas. In the Danish case the subsidisation of the energy intensive industries has not been through subsidising energy use, but has in a very limited number of cases been directed through other channels as capital support. In general industrial policy directed at conserving heavy industries in Denmark been not been especially emphasised.

4. Export opportunities from new and renewable energy technologies

New energy technologies introduced in Denmark have led to considerable contributions to export performance. This is the case for wind turbines, where Denmark has been a major actor in international markets. The market share is close to 50%.



Source: Danish Wind Turbine Manufacturers Association
1997: Estimate by the Danish Wind Turbine Manufacturers Association

Figure 2 Turnover for Danish wind turbine manufacturers

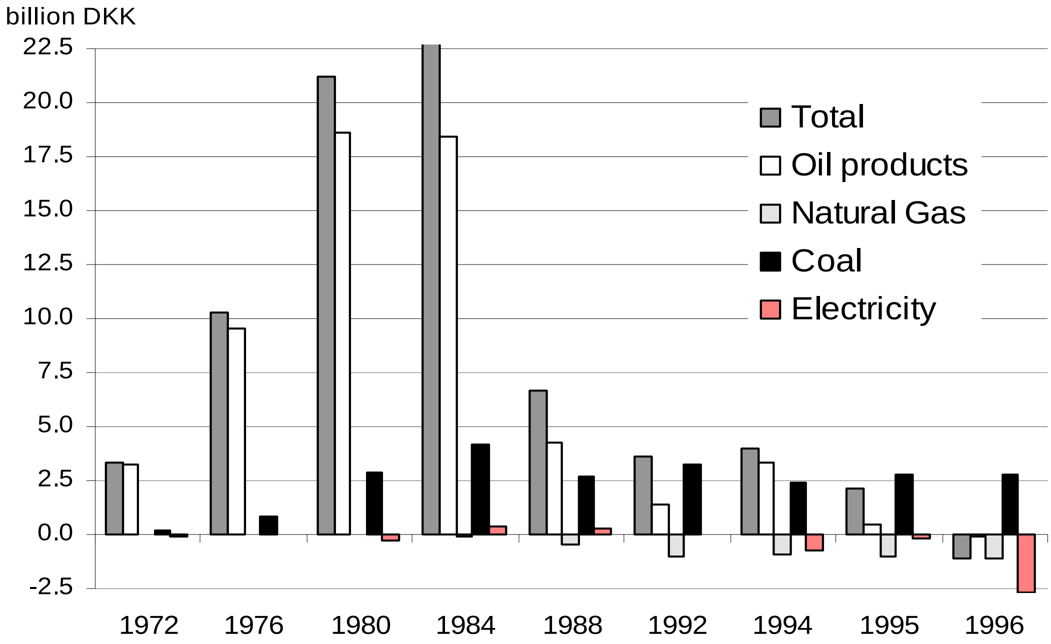
District heating systems especially pipelines have a long tradition in Denmark and this technology have been improved partly based on the public support of expanding district heating in Denmark. Denmark has one of the two largest manufactures of pre-insulated pipes in the world. The exports from the four largest producers in Denmark amount to 1.4 billion DKK in 1997. Exports of pumps, heating controls etc. from other producers related to district heating should be added to this figure.

Some export success has been recorded for cleaning technologies related to specific power producing technologies.

Consulting in the field of renewable energy is a positive contributor to service balances. This has been supported by the international reputation of the Danish case as a very "green" and environmental friendly policy. Also a very long tradition for detailed energy planning and especially the implementation of renewable energy has contributed to export opportunities for consulting firms and institutions. Some of the consulting activities have been tied to bilateral aid activities to developing countries or countries in transition. But also in the field of fully commercial projects the consultants have been successful.

5. Trade in energy commodities

Denmark has experienced major shifts in the trade with energy commodities. Originally nearly 100% reliant on foreign resources the Danish economy is today (1997) more than self-sufficient (125%) in oil products and even self-sufficient (101%) in total energy consumption.



Source: Danish Energy Agency

Figure 3 Net import of energy commodities

Oil products were the main source of the very large trade deficits in energy commodities until the mid- eighties. The shift from oil towards coal in the power sector and the reduction of liquid fuels in manufacturing industries contributed to a reduction of the import costs of oil products. The fall of oil prices in the mid-eighties also contributed to this reduction of oil import costs. Danish extraction activities increased very much from then and today the country is more than self reliant in oil products.

Natural gas has contributed to reduced imports of oil products and has to some and increasing extent been exported.

Electricity trade has traditionally been with Scandinavian countries and Germany. The size of trade has been determined by seasonal and climatic conditions. Recently the yearly change in trade flows has been very large and has caused production changes from +50% to –50%. This is partly technological dependent as investment in transmission capacities determines the possible sizes of daily transmissions. Also expansion of hydropower has created more scope for trade variation and especially the expansion of wind power in Denmark could benefit from the connection to hydropower resources.

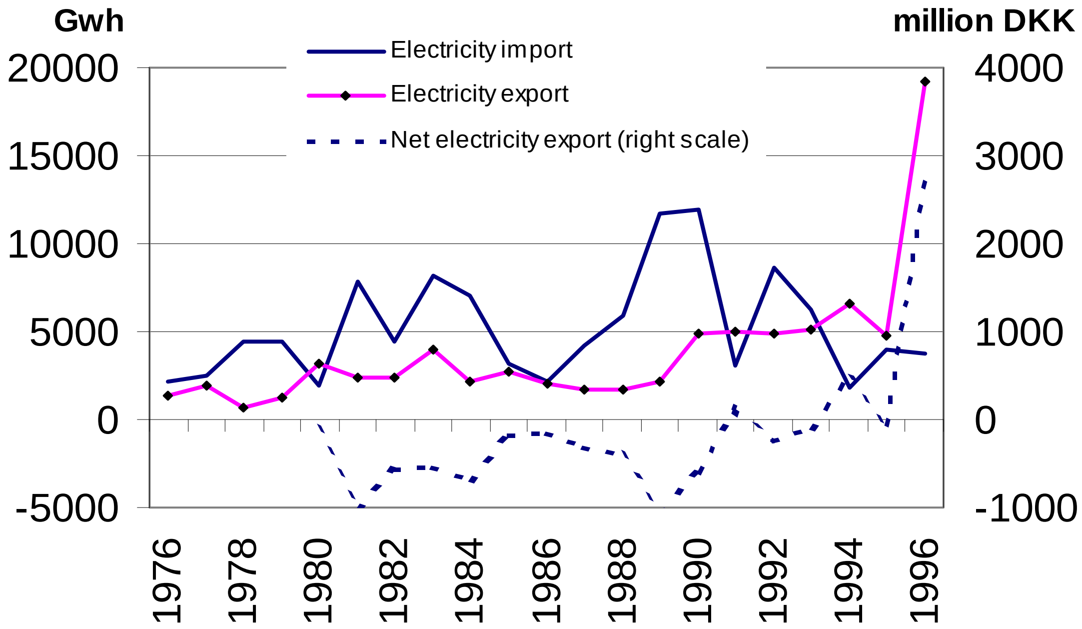


Figure 4 Trade in electricity

Trade in electricity has for many years resulted in a deficit both in physical terms and in fiscal terms. The size of the deficit has not been very big and has mainly been a result of the availability of periodically cheap hydropower from Norway and nuclear power from Sweden combined with a lack of competitors on the demand side. This trade pattern might change as the transmission capacities between Scandinavia and northern Europe is being expanded rapidly and the liberalisation of electricity markets increases the number of buyers. The surplus in electricity trade recorded in recent years (1991, 1994 and 1996) has been caused by lack of rain in Scandinavia and to some extent temporary unavailability of nuclear power plants.

The value of electricity trade has historically been very cheap imports and relatively high prices on exports. This picture will probably change towards a more equal price mainly due to an expected higher import price. The extreme case of 1996 with net exports of 2.7 billion DKK will not be the main picture in the future, but Danish producers will continue to benefit at times of low water resources in Scandinavia. This export revenue is of course matched by increased imports of coal and oil products that were also used for power production in the extreme year of 1996.

6. Concluding remarks

Energy technologies in a broader meaning has had an impact on trade patterns. This impact has been direct in the case of exporting energy technology equipment as wind turbines and district heating pipelines. The indirect effect through energy technology change and impact on competitiveness can be seen in the relative decline of the energy intensive industries of Denmark.

The relative energy intensive manufacturing industries of Denmark have experienced a stagnation of production and much slower export growth than the average of manufacturing. The number of industries with high energy intensity have also declined and hereby the production share of these four energy intensive industries are just 1.5% of total manufacturing production.

Exports of products that are related to new energy technologies have been rising fast. The examples of wind turbines and district heating pipes show that Danish producers have captured very large shares of the world market. Exports of just these two goods constitute more than 2% of total manufacturing exports.

In the field of trade with energy commodities the period from 1966 to 1992 includes major shifts in the fuel technology of the Danish economy. A shift from liquid fuels towards coal around 1980 resulted in a coal-based combined heat and power sector which is relatively robust to international competition in a rising market of electricity trade. The future trade in electricity could be off a substantial value as the recent figures suggest and the technological developments in this sector will have a large impact on trade in this commodity.

Altogether the issue of energy technology and trade developments seem to be related. The effect of the general competitive position from changing energy technologies will be rather limited as the Danish manufacturing industries have a very small share of energy in total production costs. Just as important are the export opportunities for the industries producing energy technology equipment for the world market.

Acknowledgements

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Appendix A: Data

Manufacturing industries	TJ/mill. DKK 1966	TJ/mill. DKK 1992	Production 1966 mill. DKK	Production 1992 mill. DKK	Electricity 1966	Electricity 1992	Liquid fuels 1966	Liquid fuels 1992	Natural gas 1992	Export 1966	Export 1992	Exp sha 19
Magazine publishing	0.14	0.13	835	751	10%	70%	52%	11%	6%	0	0	0
Other publishing	0.15	0.13	541	1289	10%	59%	53%	9%	5%	0	0	0
Knitting mills	0.53	0.16	1259	1998	33%	68%	51%	8%	2%	352	1192	60
Manufacture of jewellery, etc.	0.16	0.16	1249	376	24%	55%	40%	12%	1%	251	131	35
Manufacture of wearing apparel	0.34	0.17	3678	3262	24%	52%	54%	18%	8%	409	1935	59
Manufacture of footwear	0.40	0.19	865	829	25%	61%	55%	16%	14%	87	258	31
Petroleum refineries	0.24	0.19	7800	13620	99%	99%	0%	0%	0%	1875	5986	44
Slaughtering etc. of pigs and cattle	0.24	0.20	18638	29959	29%	67%	60%	23%	5%	10725	19541	65
Manuf. of telecommunication equipment	0.81	0.22	896	5537	19%	70%	66%	9%	11%	311	3465	63
Newspaper printing and publishing	0.23	0.23	3164	2933	38%	77%	20%	2%	1%	48	42	1
Reproducing and composing services	0.42	0.23	285	1080	33%	78%	21%	3%	0%	10	87	8
Professional and measuring equipment	0.21	0.23	734	4084	37%	70%	36%	9%	7%	436	3178	78
Book and art publishing	0.31	0.24	808	573	11%	58%	61%	9%	5%	0	0	0
Manuf. of made-up textile goods	0.30	0.28	316	1153	27%	57%	49%	19%	8%	41	428	37
Other printing	1.03	0.29	321	1087	34%	69%	45%	3%	3%	7	185	17
Manuf. of other electrics supplies	0.74	0.32	3536	5008	39%	64%	42%	19%	2%	770	1796	36
Processing of fish	0.29	0.33	1267	5816	40%	71%	41%	18%	4%	921	4606	79
Poultry killing, dressing, packing	0.94	0.33	575	2025	38%	76%	51%	16%	2%	375	1108	55
Manuf. of toys, sporting goods, etc.	0.84	0.33	947	3147	18%	72%	66%	9%	2%	357	2154	68
Manufacture of soap and cosmetics	0.73	0.33	759	1227	16%	53%	77%	30%	6%	112	612	50
Manufacture of household machinery	0.44	0.35	561	2072	48%	63%	36%	28%	2%	163	1470	71
Manuf. of chemical products n.e.c.	1.67	0.35	484	1032	13%	52%	81%	37%	0%	137	426	41
Ship building and repairing	0.51	0.36	5466	6634	35%	73%	44%	18%	1%	2219	3865	58
Manuf. of refrigerators, accessories	0.78	0.38	4400	12743	22%	64%	73%	19%	6%	1607	7296	57
Tobacco manufactures	0.59	0.38	1049	977	30%	69%	53%	15%	13%	81	317	32
Manuf. of metal cans and containers	0.94	0.40	955	1797	28%	64%	57%	9%	23%	61	512	29
Manufacture of industrial machinery	0.52	0.40	2855	4855	32%	59%	54%	26%	4%	1775	3123	64
Railroad and automobile equipment	0.57	0.41	2068	2546	22%	63%	55%	18%	7%	310	1255	49
Dairies	0.64	0.42	10152	11868	22%	55%	72%	30%	7%	3787	4928	42
Manuf. of structural metal products	1.23	0.43	1812	6719	21%	66%	59%	17%	6%	303	2404	36
Bookbinding	0.20	0.44	318	433	34%	77%	25%	3%	2%	8	51	12
Manuf. of electrical home appliances	0.78	0.45	308	411	29%	56%	61%	32%	7%	112	203	49
Offset printing	0.43	0.47	833	2084	19%	42%	52%	4%	38%	51	274	13
Manuf. of agricultural machinery	0.68	0.47	1373	1755	16%	50%	73%	27%	6%	615	1100	63
Repair of machinery	0.87	0.50	2045	2430	12%	46%	66%	7%	4%	0	0	0
Manuf. or paints and varnishes	0.54	0.50	905	1058	20%	59%	71%	18%	8%	185	439	41
Chocolate and sugar confectonery	0.48	0.50	989	2129	48%	59%	40%	26%	5%	154	824	39
Manuf. of paper containers, wallpaper	1.01	0.53	1892	4338	22%	63%	69%	14%	19%	194	1214	28
Processing of fruits and vegetables	0.40	0.53	909	2064	21%	51%	63%	38%	9%	132	641	31
Cake factories	1.10	0.53	506	1540	14%	58%	62%	31%	7%	127	890	58
Book printing	0.36	0.54	2037	2158	27%	32%	42%	54%	2%	118	379	18
Margarine manufacturing	0.73	0.55	589	683	25%	48%	66%	31%	15%	22	217	32
Manuf. of wooden furniture, etc.	0.52	0.56	3231	6206	24%	52%	52%	8%	5%	736	4141	67
Cordage, rope and twine industries	0.96	0.58	567	521	45%	73%	49%	6%	12%	156	267	51
Manuf. of other fabricated metal products	0.95	0.60	3458	5862	27%	69%	62%	15%	7%	881	2079	35
Ice cream manufacturing	1.33	0.60	204	976	47%	72%	31%	6%	0%	9	404	41
Manufacture of metal furniture	1.05	0.62	344	1503	14%	55%	59%	23%	13%	69	627	42
Manufacture of cycles, mopeds, etc.	1.40	0.63	341	591	16%	33%	72%	13%	49%	67	287	49
Manufacture of drugs and medicines	0.79	0.66	789	5599	55%	54%	38%	38%	4%	483	4535	81
Grain mill products	0.77	0.67	1069	1049	54%	85%	41%	4%	9%	73	278	26

Appendix A: Data (continued)	TJ/mill. DKK	TJ/mill. DKK	Production 1966	Production 1992	Electri-city	Electri-city	Liquid fuels	Liquid fuels	Natural gas	Export 1966	Export 1992	Exp sha
Manufacturing industries	1966	1992	mill. DKK	mill. DKK	1966	1992	1966	1992	1992			19
Manuf. of basic plastic materials	3.35	0.68	636	3991	25%	87%	7%	7%	4%	213	2166	54
Manuf. of accumulators and batteries	0.65	0.76	312	141	38%	88%	49%	8%	0%	111	92	65
Oil mills	1.75	0.78	1232	1849	8%	47%	90%	46%	7%	419	776	42
Bread factories	0.78	0.78	740	907	16%	46%	68%	30%	6%	18	95	10
Processed cheese, condensed milk	1.11	0.81	1429	2896	16%	37%	76%	40%	15%	1185	2013	70
Manuf. of plastic products n.e.c.	0.83	0.85	1166	5042	61%	74%	34%	8%	15%	306	2203	44
Manufacture of leather products	0.95	0.85	545	261	19%	47%	67%	37%	12%	74	107	41
Manufacture of wood products, ex. furnit.	1.87	0.98	2892	5107	42%	29%	44%	10%	0%	587	2031	40
Manufacture of food products	1.80	0.99	538	2518	48%	21%	45%	8%	37%	146	1338	53
Manuf. of earthenware and pottery	2.42	1.10	517	235	15%	33%	46%	21%	4%	138	159	67
Spinning, weaving etc. textiles	1.92	1.12	2278	2354	23%	56%	74%	25%	17%	410	1168	50
Tyre and tube industries	2.24	1.13	140	234	7%	46%	79%	40%	0%	0	47	20
Bakeries	0.88	1.20	2978	1561	12%	67%	66%	10%	6%	0	0	0
Non-ferrous metal casting	1.37	1.23	210	376	15%	72%	78%	23%	3%	22	126	34
Concrete products and stone cutting	0.68	1.29	2317	2706	29%	25%	46%	26%	32%	111	654	24
Manuf. of rubber products n.e.c.	2.14	1.31	507	602	33%	55%	64%	23%	20%	146	410	68
Fish meal manufacturing	2.41	1.32	480	2347	10%	36%	89%	21%	28%	275	1161	49
Distilling and blending spirits	8.64	1.35	248	318	4%	25%	62%	32%	11%	52	114	36
Breweries	1.52	1.39	2381	4598	9%	31%	81%	50%	9%	559	1110	24
Manuf. of glass and glass products	12.28	1.63	500	839	9%	50%	88%	8%	39%	58	264	31
Manuf. of basic industrial chemicals	2.45	1.71	768	4469	19%	62%	80%	26%	8%	480	3460	77
Manuf. of fertilizers and pesticides	4.02	1.75	759	894	42%	65%	53%	18%	16%	70	328	37
Sugar factories and refineries n.e.c.	2.10	2.20	922	2013	6%	7%	81%	27%	0%	126	844	42
Manuf.of asphalt and roofing cater.	2.26	2.33	830	1261	17%	22%	76%	55%	21%	48	284	22
Iron and steel casting	2.69	2.42	567	656	30%	85%	42%	6%	1%	72	246	38
Non-metallic mineral products n.e.c.	5.67	2.55	883	1500	14%	38%	66%	7%	9%	207	706	47
Manuf. of prepared animal feeds	2.92	2.61	714	2120	25%	35%	70%	21%	14%	204	615	29
Iron and steel works	10.10	3.10	998	1383	8%	83%	84%	2%	14%	367	890	64
Manuf. of pulp, paper, paperboard	5.60	5.30	838	941	22%	42%	71%	18%	9%	97	416	44
Manuf. of structural clay products	6.78	6.50	907	410	16%	19%	67%	11%	18%	168	194	47
Manuf. of cement, lime and plaster	16.74	14.20	871	856	13%	12%	41%	13%	1%	124	274	32

Energy demand, structural change and trade:
A decomposition analysis of the Danish manufacturing industry*

Henrik Klinge Jacobsen
Risø National Laboratory, Systems Analysis Department, henrik.jacobsen@risoe.dk

Abstract

This paper examines the relation between trade patterns and energy consumption in manufacturing industries. An input-output decomposition method is used to decompose the change in industrial energy consumption for Denmark into six components, of which three are trade-related. Trade-induced changes in energy consumption have important implications for issues such as international distribution and regulation of energy consumption and emissions. It is shown that a structural change in foreign trade patterns can increase domestic energy demand. This is contrary, however, to what might be expected for a small industrialised country, which is presumed to export products that intensively use inputs of skilled manpower as well as research and development. Finally, calculations carried out at different levels of aggregation are compared. The findings here demonstrate the importance of large variations in energy intensities among subsectors for the calculation results.
JEL classification: C67, Q4
Keywords: decomposition, energy demand, trade

1. Introduction

Trade patterns are changing as a result of the international specialisation of production and the increased integration of world economies. This is especially evident for small open economies such as the Danish one. In 1966 30.1% of Danish manufacturing production was exported; by 1992 exports had increased sharply to 47.4% of manufacturing production. The same trend applies to the share of domestic final demand for manufactured goods that is imported. For 1966 the imported share of domestic final demand was 31.8%, which was increased to a share of 46.4% in 1992.

The change in trade pattern reflected in these figures has important implications for the environment and for the use of resources in the economy. This study focuses on the implications for energy demand. The energy demand for manufacturing production in the same period rose only 7.1%, as the increase of production was offset by a 40% decline in energy intensities.

In this paper the importance of change in trade patterns for the energy consumption by production sectors is addressed by using an input-output decomposition method. Decomposition analyses of energy demand have been performed for a large number of countries and are based upon a large number of different decomposition methods. In here the change in energy consumption by Danish industries during the period 1966-1992 is decomposed into six components The paper focuses on quantifying the effects of three trade components, for the aggregate manufacturing sector as well as for the individual subsectors of manufacturing. The variation in the trade component among

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manufacturing industries is examined and compared with the energy intensity and characteristics of the individual industry.

The **first** trade component analysed is the imported share of domestic final demand. The rise in import shares has decreased Danish energy consumption. However, this corresponds to a rise in the **second** component, namely the share of Danish production that is exported. This component has contributed to increased Danish energy consumption. The **third** trade component is the imported share of total inputs to Danish production, which has also been rising during the examined period. The importance of trade in the decomposition results is compared with the common finding in decomposition analyses, namely that the intensity and level of final demand are the main contributors to change in energy consumption.

Energy demand and its environmental implications are widely discussed issues also in relation to trade and globalisation. The expected effect of a change in trade pattern for an industrialised country such as Denmark is a decline in aggregate energy intensity as induced by specialisation in high-tech industries and in industries with a high content of R&D. Apart from this effect, it is expected that a change in the composition of final demand will move production towards a larger share for the service sectors. The combined effect of this shift in production is anticipated to be a reduction of energy demand caused by the change in trade patterns. The analysis carried out for Denmark moderates such a conclusion in that the effect from the change in trade volume (balance of trade) can dominate other effects totally.

An interesting issue arises as to whether some part of the decline in aggregate energy intensity is caused by a change in the trade pattern. This issue is addressed by analysing the detailed data for the manufacturing industries. Two input-output calculations are compared; one including all the 117 industries and another for 27 aggregated industries. The results illustrate the importance of the aggregation level, especially when energy intensities differ very much among the subsectors.

2. Major economic variables and trade in Denmark 1966-1992

Energy consumption for production in Denmark is caused partly by the development of the real variables shown in Table 1. Export and import shares have changed considerably over the period and these changes can be an important explanation both for aggregate changes in energy consumption and for different developments among the various industries.

	1966 mill. DKK	1992 mill. DKK	change 1966-92
Domestic final demand	239709	383002	60%
Total exports	60531	202684	235%
Total imports	72138	151528	110%
Domestic final demand for manufactured goods	60669	83975	38%
Manufacturing production	132914	236200	78%
Share of manufacturing production that is exported	30.1%	47.4%	17.3
Import share of domestic final demand – manufactured goods	31.8%	46.4%	14.6
Import share of production inputs – manufactured goods	31.8%	36.2%	4.4

Table 1 Change in major economic variables 1966-1992

During this period, exports have increased much more rapidly than imports, and have increased about four times faster than the domestic final demand. By the end of this 27-year time frame there had been a change from a rather large trade deficit to a substantial trade surplus. From a deficit of around 30% of exports in real terms for 1966 the trade balance has improved to a surplus of around 25% of exports for 1992. This change has large implications for the Danish production and the corresponding energy demand. Is the trade impact evenly distributed over industries with different energy intensities? Or is it mainly sophisticated industries with relatively low energy intensities that are responsible for the improvement in trade figures?

The changing trade patterns have influenced energy demand in industry in three ways:

- Rising import shares for inputs to manufacturing production have decreased the manufacturing industries energy demand.
- A rise in the share of Danish production that is exported has increased energy demand.
- Rising import shares as a percentage of domestic final demand that is imported have decreased the Danish manufacturing industries energy demand.

The net result depends very much on the energy intensities of the industries that are responsible for these aggregated trade figures. Therefore the disaggregated pattern of trade changes must be examined and the decomposition analysis must be conducted at the disaggregated level.

3. Energy input and change in trade shares for Danish industries

The Danish industries are on average energy extensive relative to international levels. It is possible that the openness of the Danish economy has contributed to a specialisation in energy-extensive industries leading to a decrease in the aggregate energy intensity of production. This analysis examines the relationship between changing trade patterns and Danish industrial energy demand. The effect on energy intensity at the disaggregated level is discussed only briefly.

In Figure 1 the change in energy consumption in Tera-Joule (TJ) is compared with the change in percentage trade shares for a number of Danish industries. Only the two first trade components are included in the Figure. The import share is the import to final demand of a good as a percentage of domestic final demand for the good. The export share is exports from a given sector as a percentage of production in that sector. The import directly for input to Danish production is not included in the import share in Figure 1, but is included as the third component in the decomposition analysis. The change in shares in Figure 1 is the relative change.

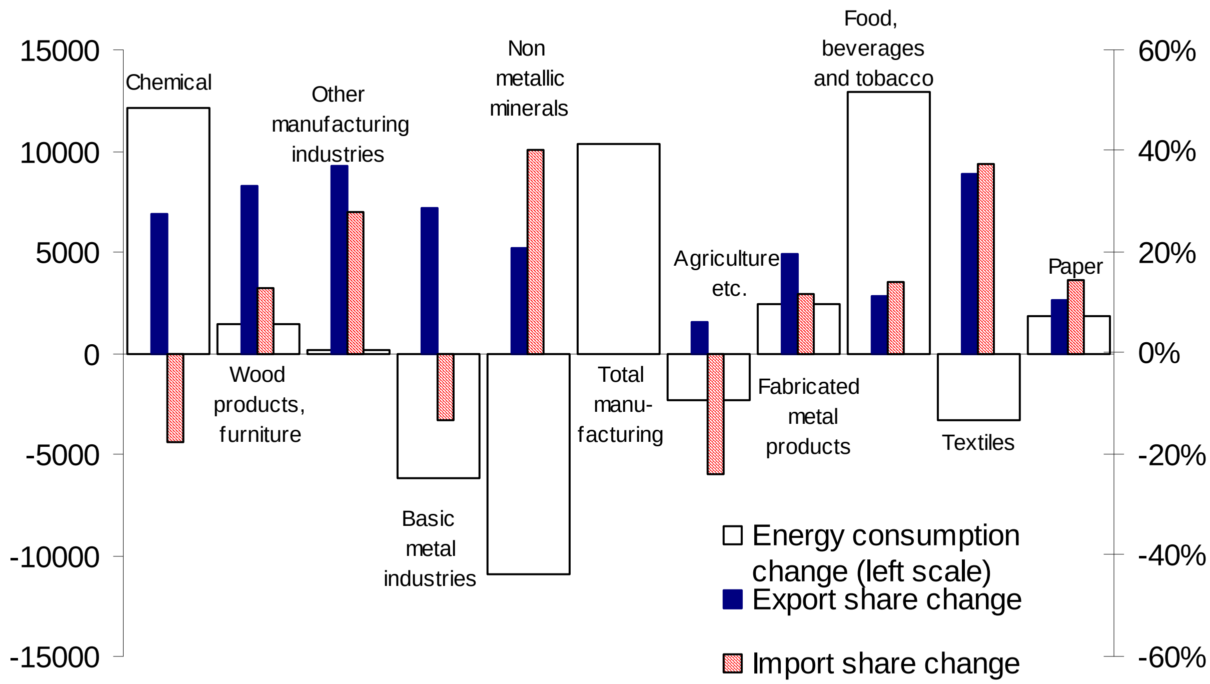

Figure 1 Change in energy consumption and change in trade 1966-1992

It is obvious from Figure 1 that the industries have behaved very differently from one another with respect to the change in energy consumption from 1966 to 1992. There are many reasons for the difference, but the important determinants are:

- Different production developments caused by a change in the composition of final demand with respect to both final demand categories and goods.
- Different development in the technology, especially the energy technology used in the sectors.
- A change in the structure of foreign trade.

This analysis focuses on the third element, which in turn includes two subelements: the change in import shares, and the change in export shares. Final demand may have shifted towards higher import shares for some goods that can be either more energy intensive than the average or less. In the same way, the import share of each input in Danish production may have shifted in a way that leads to either more domestic energy input in production or less. The effect on production and the corresponding effect on energy demand of both these structural changes of imports are examined in this paper. The effect of an import share change must be compared to that from a change in export share occurring in the same period. The inclusion of export share in the analysis raises some methodological questions of how to define export shares appropriately.

Structural change in foreign trade patterns and the increased participation in the international economy by Danish industry have influenced the production structure and hereby the demand for energy. All industries in Figure 1 have increased their export share. Hereby energy consumption associated with producing exports has increased faster than energy consumption associated with production for the domestic market. Some industries with large increases in energy consumption have increased their market share in domestic final markets as well. This is especially the case for the chemical industry, which is the reason for a very large foreign trade contribution to the increase in energy consumption of this sector, as will be seen later. In other sectors, such as textiles, the trade developments show large increases in both export and import shares, which indicates product specialisation and no net contribution to energy consumption from trade. However, the importance of import shares in domestic final demand differs from one sector to another depending on the characteristics of the production as to whether final or intermediate goods are produced. As will be exemplified below, for some industries the import share for intermediate inputs can contribute much more to energy consumption changes than the import share in final demand.

4. Decomposition analysis

A large number of studies have analysed changes in energy demand or emissions by decomposing the change into a number of components. The main components represented in these studies are level of final demand, composition of final demand, input-output structure and energy intensity. For studies of emissions the composition on energy types and emission factors are also included. Studies of a larger number of countries have often restricted the number of components to e.g. production and energy intensity for decomposing energy consumption change.

Decomposition analyses of energy demand developments often show that structural change is of minor importance relative to the change in energy intensity and the level of final demand. A number of decomposition studies of energy demand and energy-related emissions have been looking at the importance of structural change. In most cases two components have been examined: the change in input-output structure and in the composition of final demand. Some studies decompose even further taking also account of the change in energy exports and imports (Mukhopadhyay and Chakraborty, 1999).

Wier (1998) decomposes changes in Danish emissions of CO_2, SO_2 and NO_x from 1966 to 1988 into six components. The study finds structural change to have a minor influence on emissions for Denmark. The level of final demand is the largest component for all emission categories. For CO_2 emissions this component was driven partly by increased production of export goods and services in the agricultural, food manufacturing and transportation sectors. This is especially interesting for a study of the importance of trade patterns for energy consumption, as CO_2 is the emission category most directly related to total energy consumption. Wier finds that the two structural components - input mix and composition of final demand - have reduced emissions of all three categories, even though their importance is less than the level of final demand, energy intensity and in the case of SO_2 also fuel mix and emission factors.

In an earlier study, which used data for the period 1966 to 1979, Pløger (1984) found the same result for energy demand. Energy consumption change is decomposed into four components of which the level of final demand contributes to an increase in energy consumption and is the absolutely dominant component. The energy intensity, input-output structure and composition of final demand all contribute to a reduction in energy consumption of which input-output structure has the smallest impact. Pløger examines domestic energy use as well as global energy content. A decomposition of global energy consumption for the production of Danish final demand shows the same results for the structural components. Input-output structure and composition of final demand are even less important for change in global energy content. Another result is that changes in imports tended to decrease the part of global energy content in final demand actually being used in Denmark.

The definition of structural change is not straightforward and it differs what is meant by structural change. Structural change can be a narrow definition limited to a change in input-output structure of production, or it can encompass a broader definition of a change in the industry composition of total production or final demand. The meaning of structural change also differs between those studies focusing on domestic energy use in production and those focusing on the global energy use associated with the domestic part of final demand. Trade has been examined in a decomposition study by Gale (1995), which investigates the trade liberalisation impact on Mexican emissions of CO_2. Results from this study suggest that the liberalisation is likely to produce a shift away from CO_2-intensive production in Mexico. In another study examining energy conservation options in household energy requirements in the Netherlands, Wilting et. al. (1999) especially address the issue of trade by distinguishing between competitive imports that are assigned the same energy intensity as embodied in domestic production and non-competitive imports where energy intensities are individually estimated. However, the Wilting et. al. study does not directly address the issue of whether changes in trade patterns explain changes in energy consumption.

Structural change of trade patterns is also an element of the overall change in the structure of the economy. Structural change of trade patterns belongs to a broad definition of structural change. The problem about trade patterns is that it is not a single component but is embodied in the other components in a standard decomposition analysis. Trade patterns are embodied in both the input-output structure (intermediate imports) and in the composition and level of final demand (import and export shares). The structural input-output term includes both a change in technology and in the share of intermediate inputs that are imported. Import shares of final demand are related to the level of final demand that creates domestic production as well as the composition of final demand for domestic production. Export share is embodied in the level of the final demand component and also in the composition of final demand.

This decomposition study focuses on the importance of the trade component for the direct energy consumption in 117 sectors in Denmark. The model applied is the static input-output model with endogenous import. Energy consumption change for these 117 sectors is decomposed into five components.

Following this, the energy consumption is given by,

$$\mathbf{e} = \left[\mathbf{I} - \left(\mathbf{A} \circ \mathbf{A}^{D}\right)\right]^{-1} \left[\left(\mathbf{D} \circ \mathbf{D}^{D}\right) \mathbf{i}_2\right] \circ \mathbf{q} \qquad (1)$$

$\mathbf{e}$ is the 117 x 1 vector with the energy consumption in TJ for all sectors
$\mathbf{A}$ is the 117 x 117 input coefficient matrix,
$\mathbf{A}^D$ is a 117 x 117 matrix with the share of inputs of domestic origin for all sectors,
$\mathbf{D}$ is a 117 x 2 matrix with absolute levels of domestic final demand and demand for exports,
$\mathbf{D}^D$ is a 117 x 2 matrix with shares for domestic origin of the two final demand categories,
$\mathbf{i}_2$ is a 2 x 1 vector with ones,
$\mathbf{q}$ is a 117 x 1 vector with energy intensities in all sectors

$\circ$ means element-wise multiplication. Hence the element (i,j) of the matrix $\mathbf{A}\circ\mathbf{B}$ is given by $a_{ij}b_{ij}$.

The $\mathbf{A}$ matrix is the total 117 x 117 input coefficient matrix including the intermediate imports. Domestic shares of inputs for all sectors and all goods are contained in the $\mathbf{A}^D$

matrix and $[\mathbf{I}-(\mathbf{A}\circ\mathbf{A}^D)]^{-1}$ is the Leontief inverse matrix. The $(\mathbf{D}\circ\mathbf{D}^D)\mathbf{i_2}$ matrix corresponds to the 117 sector composition of total final demand for domestic production.

One important trade component is still missing: It is the export impact embodied in the level component **D**. The level component has to be divided between an underlying level component and one derived from a change in the export "dependence". Some measure of export share is needed. Using changes in export and domestic final demand shares would not yield any result for the impact of change in export dependence. Another option is to look at total exports relative to domestic final demand. But this measure does not include the effect of a change in the global input-output structure (technology), which must be assumed to have an impact on export demand for intermediate inputs. Also, to use the level of exports would be misleading as it includes a component of final demand level. By using the export level the importance of increasing export dependence would be greater than if the previous measure were used instead.

In this analysis the level component is split into level and export share not by just looking at the composition of final demand categories represented by shares, but by relating export demand to domestically created production. This measure, which includes the input-output structure, moderates the technical problems associated with the disaggregated data. When disaggregated final demand data for 117 output sectors are examined the method of using export relative to domestic final demand in the base year becomes critical. Two problems arise here: For some industries domestic final demand can be very small and a small absolute change in domestic demand could induce a large change in exports relative to domestic demand. This could be the case if an intermediate product is being examined. In the case where the energy intensity for this product is high, the aggregate result can be a substantial impact on aggregate energy consumption from a small change in trade. The other and related problem is the change in stocks. If a single year is used for decomposition, changes in stocks can have a large impact on export shares even though in some cases the change occurs only in stocks of export goods. Some export-intensive industries have large stocks due to vulnerable exports.

Thus, the change in stocks is excluded from domestic final demand and the export share measure is export relative to domestically created production.

$$\mathbf{x}^S = \mathbf{x}.\circ\div[\mathbf{I}-\mathbf{A}]^{-1}\bar{\mathbf{d}} \qquad (2)$$

x is the export demand for 117 output goods of domestic origin,
$\bar{\mathbf{d}}$ is the domestic final demand for 117 goods, excluding the change in stocks, and
A is the 117 x 117 coefficient matrix of all inputs
∘÷ means elementwise division.

The change in energy consumption for the 117 sectors is then decomposed into six elements:

$$\mathbf{e}_t - \mathbf{e}_{t-1} = \Delta\mathbf{A} + \Delta\mathbf{A}^D + \Delta\mathbf{D} + \Delta\mathbf{x}^S + \Delta\mathbf{D} + \Delta\mathbf{q} \qquad (3)$$

where
$\Delta\mathbf{A}$ is the input structural effect,
$\Delta\mathbf{A}^D$ is the effect of changes in domestically produced share of inputs,

$\Delta\mathbf{D}$ is the level of final demand effect,
$\Delta\mathbf{D}^D$ is the effect of changes in the domestically produced share of final demand,
$\Delta\mathbf{q}$ is the effect of energy intensity changes and
$\Delta\mathbf{x}^S$ is the effect of changes in export shares

Decomposition is carried out by using the method of Betts (1989) and Fujimagari (1989). This Input-Output Structural Decomposition Analysis (IO SDA) method is one of the many decomposition methods used. Another common method is the Divisia Index method. Ang (1995) includes a survey of multilevel decomposition studies of industrial energy consumption as well as an illustrative survey of different decomposition methodologies.

In the method applied in this paper the components are changed one by one. Two computations are carried out in which the components are changed in reverse order and the average of the explanations in the two computations is used to quantify the explanation from each component. Dietzenbacher and Los (1998) refer to this method as the average of two polar forms and compare this average to the average of all exact forms. They find that the two averages are remarkably close[1] giving an argument for computing only the simple average applied in this study of trade patterns. However, they find great variability in explanations from four components depending on which exact form that is used and they argue that the range (standard deviation) of results for each component should be computed using all exact forms to give a more complete picture of decomposition results. The present study does not compute all exact forms and therefore no range results are given but the results of the two polar forms applied exhibit large differences for some components.

The interaction effect and thereby the dependence of the result on the order of the components become larger as more components are included implying that variability in the decomposition results here are even larger than in the Dietzenbacher and Los study. The advantage of this method is that it results in an exact decomposition of the change in energy consumption for production.

The decomposition into six components is carried out according to:

$$\begin{aligned}\Delta\mathbf{A} = \tfrac{1}{2}&\Big[\big[\mathbf{I}-(\mathbf{A}_t\circ\mathbf{A}_{t-1}^D)\big]^{-1}-\big[\mathbf{I}-(\mathbf{A}_{t-1}\circ\mathbf{A}_{t-1}^D)\big]^{-1}\Big]\big[(\mathbf{D}_{t-1}\circ\mathbf{D}_{t-1}^D)\,\mathbf{i}_2\big]\circ\mathbf{q}_t\ + \\ \tfrac{1}{2}&\Big[\big[\mathbf{I}-(\mathbf{A}_t\circ\mathbf{A}_t^D)\big]^{-1}-\big[\mathbf{I}-(\mathbf{A}_{t-1}\circ\mathbf{A}_t^D)\big]^{-1}\Big]\big[(\mathbf{D}_t\circ\mathbf{D}_t^D)\,\mathbf{i}_2\big]\circ\mathbf{q}_{t-1}\end{aligned} \tag{4}$$

$$\begin{aligned}\Delta\mathbf{A}^D = \tfrac{1}{2}&\Big[\big[\mathbf{I}-(\mathbf{A}_{t-1}\circ\mathbf{A}_t^D)\big]^{-1}-\big[\mathbf{I}-(\mathbf{A}_{t-1}\circ\mathbf{A}_{t-1}^D)\big]^{-1}\Big]\big[(\mathbf{D}_{t-1}\circ\mathbf{D}_{t-1}^D)\,\mathbf{i}_2\big]\circ\mathbf{q}_t\ + \\ \tfrac{1}{2}&\Big[\big[\mathbf{I}-(\mathbf{A}_t\circ\mathbf{A}_t^D)\big]^{-1}-\big[\mathbf{I}-(\mathbf{A}_t\circ\mathbf{A}_{t-1}^D)\big]^{-1}\Big]\big[(\mathbf{D}_t\circ\mathbf{D}_t^D)\,\mathbf{i}_2\big]\circ\mathbf{q}_{t-1}\end{aligned} \tag{5}$$

[1] Table 6 in their study shows that this is the case for the average of all sectors and the small standard deviations in the table suggest that it is also the case for individual sectors.

$$\Delta \mathbf{D}^{D} = ½\left[\mathbf{I} - (\mathbf{A}_{t-1} \circ \mathbf{A}_{t-1}^{D})\right]^{-1} \left[\mathbf{D}_{t-1} \circ (\mathbf{D}_{t}^{D} - \mathbf{D}_{t-1}^{D})\ \mathbf{i}_{2}\right] \circ \mathbf{q}_{t} + ½\left[\mathbf{I} - (\mathbf{A}_{t} \circ \mathbf{A}_{t}^{D})\right]^{-1} \left[\mathbf{D}_{t} \circ (\mathbf{D}_{t}^{D} - \mathbf{D}_{t-1}^{D}) \mathbf{i}_{2}\right] \circ \mathbf{q}_{t-1} \tag{6}$$

$$\Delta \mathbf{q} = ½\left[\mathbf{I} - (\mathbf{A}_{t-1} \circ \mathbf{A}_{t-1}^{D})\right]^{-1} \left[(\mathbf{D}_{t-1} \circ \mathbf{D}_{t-1}^{D})\ \mathbf{i}_{2}\right] \circ (\mathbf{q}_{t} - \mathbf{q}_{t-1}) + ½\left[\mathbf{I} - (\mathbf{A}_{t} \circ \mathbf{A}_{t}^{D})\right]^{-1} \left[(\mathbf{D}_{t} \circ \mathbf{D}_{t}^{D}) \mathbf{i}_{2}\right] \circ (\mathbf{q}_{t} - \mathbf{q}_{t-1}) \tag{7}$$

The export component is calculated as

$$\Delta \mathbf{x}^{S} = ½\left[\mathbf{I} - (\mathbf{A}_{t-1} \circ \mathbf{A}_{t-1}^{D})\right]^{-1} \left[\bar{\mathbf{d}}_{t-1} \circ (\mathbf{x}_{t}^{S} - \mathbf{x}_{t-1}^{S})\right] \circ \mathbf{q}_{t} + ½\left[\mathbf{I} - (\mathbf{A}_{t} \circ \mathbf{A}_{t}^{D})\right]^{-1} \left[\bar{\mathbf{d}}_{t} \circ (\mathbf{x}_{t}^{S} - \mathbf{x}_{t-1}^{S})\right] \circ \mathbf{q}_{t-1} \tag{8}$$

The level of demand component is then calculated as the total level of final demand minus the export share component

$$\Delta \mathbf{D} = \left[\mathbf{I} - (\mathbf{A}_{t-1} \circ \mathbf{A}_{t-1}^{D})\right]^{-1} \left[\left((\mathbf{D}_{t} - \mathbf{D}_{t-1}) \circ \mathbf{D}_{t}^{D}\right)\mathbf{i}_{2}\right] \circ \mathbf{q}_{t} + \left[\mathbf{I} - (\mathbf{A}_{t} \circ \mathbf{A}_{t}^{D})\right]^{-1} \left[\left((\mathbf{D}_{t} - \mathbf{D}_{t-1}) \circ \mathbf{D}_{t-1}^{D}\right)\mathbf{i}_{2}\right] \circ \mathbf{q}_{t-1} - \Delta \mathbf{x}^{S} \tag{9}$$

The decomposition method used here can be compared to that given by Wier (1998), where the average is taken for two calculations using either base year or end-year weights for all components. By employing this method for decomposition the explanation includes a residual. The residual will be quite small for the explanation of total energy consumption in the economy; however, it can be quite large if examined for a single sector. An advantage of the method is the independence of the order of components in the calculation. In contrast, the decomposition method used by Pløger (1984) is biased in the way that base year and current year weights are chosen arbitrarily for the individual component, but differently to ensure a full decomposition without a residual.

To use the definition of structural change and structural change in trade patterns outlined above will tend to moderate the explanation from the level of final demand and to a smaller extent also the explanation from composition of final demand. Also, the explanation from input-output structures must be expected to decline. The impact of export and import shares must be expected to be of opposite sign and the sum of the aggregate effects might very well be expected to be of a moderate size.

5. Data and decomposition results

The decomposition is based on Danish national accounts and energy balances as published in Statistics Denmark (1996)[2]. The available data have a time span of 27 years

[2] The detailed tables can be purchased from Statistics Denmark but are not published in print.

from 1966 to 1992[3], which is a period that includes both significant shifts in energy technology and energy intensity as well as foreign trade structure. The calculations are carried out for the change in direct energy consumption from 1966 to 1992 measured in TJ. All national account figures are in fixed 1980 prices. Energy matrices basically contain 25 types of primary and converted energy and cover the 117-sector National Account classification. Only total energy input figures (in calorific terms) are used in this decomposition and the composition on energy types and fuels etc. are not addressed. Decomposition for four sub-periods has also been conducted and the main results for the total economy and for manufacturing are reported in Table 2. Percentages show the contribution of each component relative to the base year energy demand. The sum of percentages for the six components equals the total change in energy demand corresponding to the full decomposition method.

Period	Level	Export share	Final import share	IO-struc-ture	IO-import share	Inten-sity	Total change	Net trade
1966-1975								
All sectors	24%	4%	-2%	5%	-5%	-7%	19%	-3%
Manufacturing	23%	8%	-3%	12%	-12%	-10%	18%	-7%
1976-1980								
All sectors	15%	7%	0%	1%	-5%	-2%	17%	2%
Manufacturing	9%	16%	0%	2%	-8%	-16%	3%	8%
1981-1985								
All sectors	15%	2%	-1%	0%	-2%	-5%	9%	-1%
Manufacturing	13%	3%	-3%	0%	-5%	-7%	1%	-5%
1986-1992								
All sectors	8%	4%	0%	-2%	0%	-19%	-10%	4%
Manufacturing	3%	7%	0%	3%	-6%	-22%	-16%	1%
1966-1992								
All sectors	60%	17%	-4%	-4%	-6%	-29%	34%	6%
Manufacturing	49%	32%	-8%	-3%	-13%	-50%	7%	11%

Table 2 Summary of decomposition results for total economy and manufacturing in four subperiods

Denmark is often characterised as a country producing and exporting processed products with a high content of research and development, skilled manpower and design, all of which are increasing with the years. The change is supposed to lead to less energy content in exports and more energy content in imports. These imports are supposed to be increasingly dominated by intermediate products for further processing and consumer goods with relatively high energy content as cars and other durable consumer goods. This way it could be supposed that the change in the structure of foreign trade leads to a reduced energy demand from industries in Denmark. This is not, however, found in the material used here.

When the results in Table 2 are examined the net trade effect change sign in the different periods, but if trade components are examined separately the contribution has the same sign in all sub-periods. Also the level and intensity components have the same sign throughout the period. For the input-output structural component there is for manufacturing in the subperiods only positive contributions, whereas the decomposition for the entire period result in a negative contribution. This is possible because in the

[3] From 1992 the matrices have been enlarged and revised for sectoral classification and disaggregation as well as for energy types. Historical time series are not yet available.

subperiod decomposition uses weights within the entire period and there has been reversals of underlying trends in io-structure and energy intensities[4].

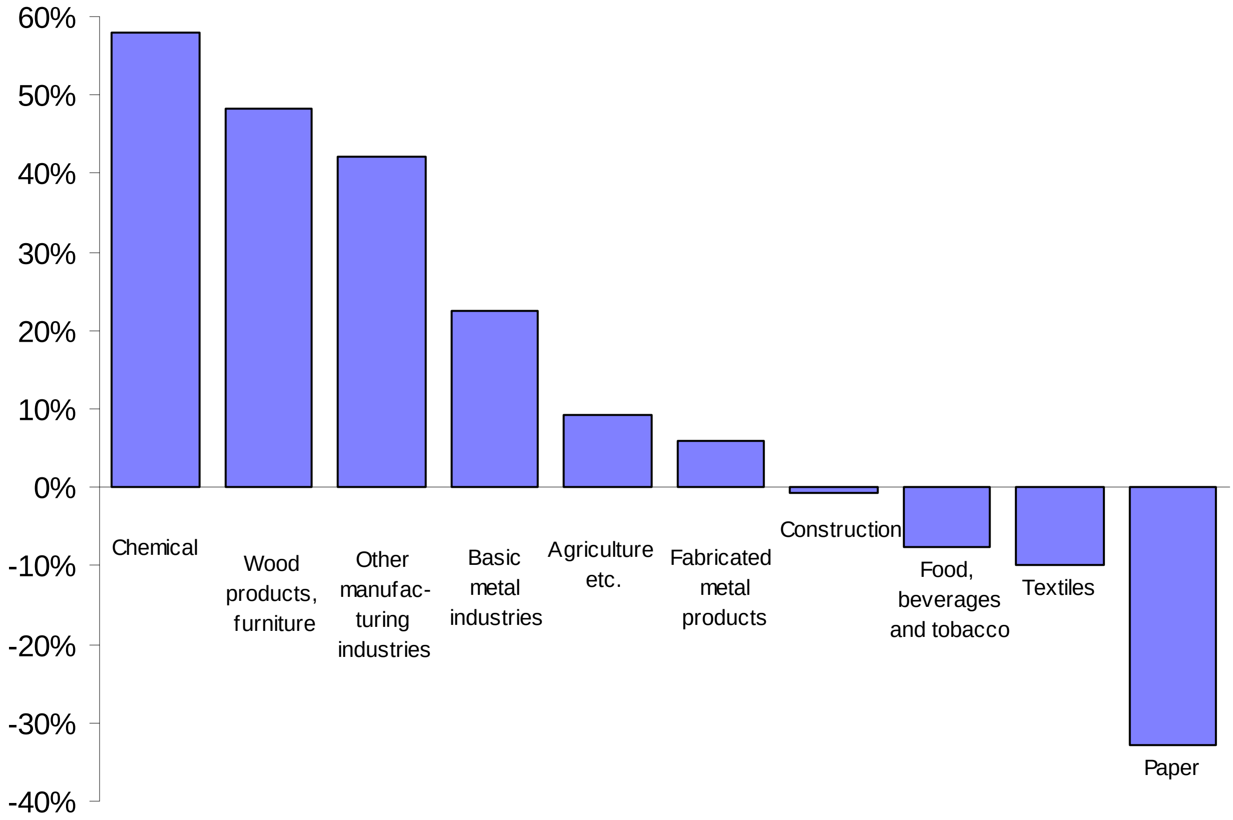

Figure 2 Net impact of trade patterns on energy consumption from 1966 to 1992

Figure 1 includes the actual changes in energy consumption for sectors, whereas Figure 2 gives the decomposition contribution from trade patterns. For basic metal industries, that have reduced energy consumption over the period by 6225 TJ, this means that other components have reduced energy consumption more than trade has increased consumption. In Table 3 where contributions from all the decomposition components are given the net trade effect for basic metal industries is +2879 TJ and energy intensity contribution is –8827 TJ.

The decomposition does not include a component for the composition of final demand and is performed by element-wise multiplication of total production and energy intensity. Decomposition without including a component of composition of final demand allows examining the importance of components for all of the 117 industries. This reveals very large variation in both the relative importance of the three trade components and in the net trade effect for the different industries. Even within the manufacturing sector, the net trade impact on energy consumption differs between a positive contribution of 60% and a negative one of 35%. This is the case for industries at

[4] The great positive contribution from io-structure in the first period is partly caused by increased use of basic plastic materials that has high energy intensity in both 1966 and 1975 but in 1992 this intensity has fallen dramatically. The io-import share shows a great negative contribution for the same period, which is also partly caused by basic plastic materials that experiences a large increase in io-import shares during the same period.

the 27-industry level. The variations are much larger at the 117 level as is clear from the table in the appendix. In the appendix results corresponding to those in Table 3 are given for all 117 sectors together with the contribution from each component relative to the 1966 energy demand.

The change in trade patterns shows marked differences in impacts on the various industries. On average, the explanation for the sum of the three components related to foreign trade has accounted for a rise of 11% for manufacturing industry energy consumption. All percentage figures given below are calculated contributions relative to energy consumption in the base year (1966).

Industry/ Component	Level	Export share	Final import share	IO-structure	IO-import share	Intensity	Total change	Net trade
Agriculture etc.	18810	6074	-519	-7567	-1527	-17574	-2303	4028
Forestry	-4	67	1	-54	9	70	89	77
Fishing	1437	3794	-1951	-1320	-396	3537	5101	1447
Mining	621	118	714	-25	95	1731	3253	926
Food, beverages and tobacco	24735	2122	-2678	3171	-2037	-12401	12911	-2594
Textiles	1711	2454	-2120	-738	-1102	-3509	-3304	-768
Wood products, furniture	1468	3786	-369	-117	-2	-3370	1397	3416
Paper	5858	2815	-986	1075	-4925	-1979	1858	-3096
Chemical	14341	11377	-174	1634	-2133	-12917	12128	9070
Non metallic minerals	3415	9563	-1325	-7924	-2487	-12211	-10969	5751
Basic metal industries	2457	6424	-289	-2733	-3256	-8827	-6225	2879
Fabricated metal products	16411	7443	-3399	1421	-2702	-16733	2442	1342
Other manufacturing industries	704	661	-172	26	-74	-1027	118	415
Electricity, gas and water	779	2	-59	-108	-37	1740	2317	-94
Construction	1641	0	-36	-2181	-43	4500	3881	-79
Wholesale and retail trade	17295	3105	-408	985	-478	-13403	7096	2219
Restaurants and hotels	4085	102	-43	-173	-18	-1486	2468	41
Transport and storage	40768	-1340	-809	-4282	-537	6373	40174	-2685
Communication	3487	0	-51	1576	-22	-3220	1769	-73
Finance and insurance	2308	-126	-19	-41	-10	3441	5553	-155
Dwellings	928	0	0	0	0	270	1198	0
Business services	4090	233	-194	3752	-85	1942	9738	-46
Private education and health	1391	0	2	-265	-5	-344	779	-3
Recreation and cultural service	1496	-53	-14	186	94	-1295	414	27
Household services	2413	0	-87	309	-46	-4213	-1624	-133
Other service	370	0	0	0	0	-114	256	0
Government services	30428	-123	-27	1499	-11	-5902	25865	-161
All Industries	203442	58498	-15012	-11896	-21735	-96919	116378	21751
Manufacturing	71099	46645	-11511	-4186	-18718	-72974	10355	16416

Table 3 Decomposition results for 27 sectors 1966-1992 (TJ contribution from component)

The relative size of the three trade components also differs very much from one industry to another. Some industries have experienced a more profound move towards world market integration than have others. Some have benefited by gaining market shares both in domestic markets and increasing export shares. Others are hurt especially by declining market shares for inputs to other industries relative to foreign competitors. In Figure 3 paper and textiles especially exhibit increasing integration with world markets as all three trade components are of considerable size. Both sectors have positive contributions to energy demand from export performance and negative impact from increasing import shares for both final and intermediate goods. Increasing import shares in final demand have especially influenced the textile industry.

The calculations have been carried out for 117 sectors. If individual sectors within the sectors presented in Figure 2 and Figure 3 are examined, the impact of trade becomes even more important. Referring to the table in the appendix with results for all 117 sectors, the data show that for some of the manufacturing industries which have experienced a large change in energy consumption the change is caused by a shift in the pattern of trade.

In the chemicals sector where the aggregate trade effect has been to increase energy consumption by nearly 60% mainly by increasing export shares without seriously increasing import shares, the chemical subsectors have behaved very differently. The sector consists of 12 subsectors of which three have expanded energy consumption considerably. These three sectors: drugs and medicine, basic industrial chemicals, and other plastic products have expanded energy consumption due to very successful export performance. At the same time, the energy intensity of each sector has declined sharply except for the last. For basic industrial chemicals this decline is caused by a structural change within the subsector not observable in the data. The activity has changed towards the production of industrial enzyme, which is much less energy intensive than the original production in the subsector.

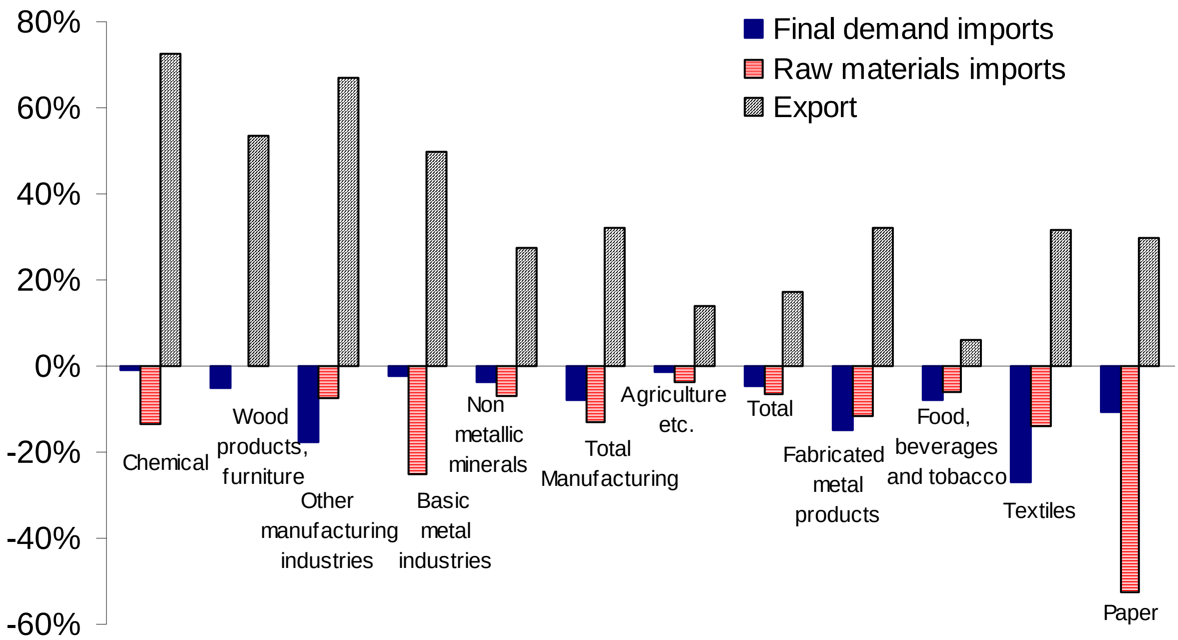

Figure 3 Export versus domestic competitive performance

One of the paper industries, namely the manufacture of paper and pulp, shows the largest difference between the aggregate paper industry and a subsector. The manufacture of pulp and paper is the industry within the paper sector with the highest energy intensity, 5.3 TJ/mill. Danish Kroner (DKK) relative to an average of 0.64 TJ/mill. DKK. This subsector has a net trade component of minus 60%, mainly as a result of increasing import shares in intermediate inputs (-87%), while the other 10 subsectors of the paper industry have a negative component of only 1%. This observation suggests that the most basic activity within a sector is the one that has been influenced to the greatest extent by the trade pattern shift. The basic production of paper and pulp has not been able to compete with imports, forcing many manufacturing plants to shut down on a number of occasions. The other industries within the paper sector are directed to a much greater extent towards domestic final demand.

The manufacture of structural clay products has experienced a decline in energy consumption of 3486 TJ. This energy-intensive industry has reduced energy intensity only slightly over the period, and it could be supposed that such a sector would be hurt by foreign competition. This has not been the case, however, as reflected in these figures, as the net effect of foreign trade is a positive contribution of 20% to energy consumption. What has happened instead is a reduction in the level of final demand, especially a reduction arising from technical changes in the way that inputs to other industries, such as construction, has reduced energy consumption by 54%. To some extent this could be a result of trade patterns if, in the case of the construction sector, the structural clay products have been replaced with imported prefabricated building parts. This analysis is unsuited to finding answers to this question.

The decomposition analysis shows that the change in trade patterns has been at least as important as the remainder of the structural change components for assessing the change in aggregate energy consumption in manufacturing industries. If the components are examined one by one, the export component proves to be the most important. This component is the reason for the positive contribution of 11% to energy consumption from trade. This is what is also reflected in the trade figures for Denmark over the period as described in Section 2.

6. Comparing results from input-output calculations at different aggregation levels

In this comparison a slightly different method from the one described in Section 4 is used to examine the effect of the combined change in all three trade components over the period 1966 to 1992. The calculation use 1966 trade shares in combination with 1992 values for all other variables in order calculate 1992 energy demand with the 1966 trade pattern. The trade shares examined are the export shares of Danish production, import shares in final demand as well as import shares for intermediate inputs in Danish production in line with the definitions used in the decomposition above. The calculations have been carried out based on the same national accounts and energy balances as in the decomposition but at two different aggregation levels. This calculation is performed as an alternative to the decomposition analysis, and also to compare the results obtained with an aggregation level of 27 industries relative to 117 industries. The aggregation aspect covered by Dietzenbacher and Los (1998)[5] is different from the aggregation aspect analysed here. They find that higher level of aggregation not necessarily reduce the variability of decomposition results. This section examines a different aggregation aspect, namely whether a different aggregation level produces different results for the aggregated sectors and the applied method is not a decomposition analysis.

The calculation of the energy input $\mathbf{e}_x$ in 1992 with 1966 import and export shares for each of the 27 and 117 industries respectively is carried out as:

$$\mathbf{e}_x = \left(\left[\mathbf{I} - \mathbf{A}_x^g\right]^{-1} \mathbf{d}_x^g\right) \circ \mathbf{q} \qquad (10)$$

where $\mathbf{A}_x^g$ is the domestic input matrix in 1992 with 1966 import shares for production inputs and each element in $\mathbf{A}_x^g$ calculated according to (11), $\mathbf{d}_x^g$ is the vector of final demand for domestically produced goods calculated according to (12) and $\mathbf{q}$ is the vector of energy intensities in domestic production. The notation for elementwise multiplication $\circ$ and elementwise division $\circ\div$ is the same as in Section 4.

[5] They investigate whether higher aggregation level for computation reduces the variability or range of decomposition results obtained by the different exact decomposition forms.

$$a^{g}_{x\,i,j} = (a^{g}_{i,j} + a^{m}_{i,j})\,\tilde{a}^{d}_{i,j} \;;\; \tilde{a}^{d}_{i,j} = \frac{a^{g}_{i,j\,0}}{a^{g}_{i,j\,0} + a^{m}_{i,j\,0}} \qquad (11)$$

$a^{g}_{i,j}$ is an element in the 1992 matrix of inputs of domestic goods, $a^{m}_{i,j}$ is an element in the 1992 matrix of imported[6] inputs and the element $\tilde{a}^{d}_{i,j}$ denotes the domestic share of inputs for 1966[7].

The final demand for domestic production $\mathbf{d}^{g}_{x}$ is calculated with 1966 import share in final demand $\overline{\mathbf{d}}^{g}_{0}$ and with adjusted export demand $(\mathbf{x}_0 \circ \mathbf{k}_x)$ based on the growth in the sum of domestic final demand and the total inputs of goods associated with this domestic final demand[8].

$$\mathbf{d}^{g}_{x} = \left[\mathbf{d}^{g}_{t} + \mathbf{d}^{m}_{t} - \mathbf{x}_t + (\mathbf{x}_0 \circ \mathbf{k}_x)\right] \circ \overline{\mathbf{d}}^{g}_{0}; \quad \overline{\mathbf{d}}^{g}_{0} = \mathbf{d}^{g}_{0} \circ\div (\mathbf{d}^{g}_{0} + \mathbf{d}^{m}_{0}) \qquad (12)$$

The domestic final demand $(\mathbf{d}^{g}_{t} + \mathbf{d}^{m}_{t} - \mathbf{x}_t)$ is adjusted by excluding the change in stocks $\mathbf{il}_t$, $\mathbf{x}$ represents the total exports. The correction factor for total exports $\mathbf{k_x}$ is the calculated 1992 domestic final demand and associated production inputs relative to the 1966 domestic final demand and associated inputs given the input output structure of each year.

$$\mathbf{k}_x = (\mathbf{d}^{g}_{t} + \mathbf{d}^{m}_{t} - \mathbf{x}_t - \mathbf{il}_t) + (\mathbf{A}^{g}_{t} + \mathbf{A}^{m}_{t})\left[\left[\mathbf{I} - \mathbf{A}^{g}_{t}\right]^{-1}(\mathbf{d}^{g}_{t} + \mathbf{d}^{m}_{t} - \mathbf{x}_t - \mathbf{il}_t)\right] \circ\div$$
$$(\mathbf{d}^{g}_{0} + \mathbf{d}^{m}_{0} - \mathbf{x}_0 - \mathbf{il}_0) + (\mathbf{A}^{g}_{0} + \mathbf{A}^{m}_{0})\left[\left[\mathbf{I} - \mathbf{A}^{g}_{0}\right]^{-1}(\mathbf{d}^{g}_{0} + \mathbf{d}^{m}_{0} - \mathbf{x}_0 - \mathbf{il}_0)\right] \qquad (13)$$

When the detailed 117 level data are used, the method of using import shares of final demand in 1966 and adjusting export with growth in final domestic demand can be crucial. As in the decomposition, this problem can generate impacts on a single industry and also for the aggregate export impact.

If the domestic final demand have increased considerably from originally very low numbers the 1992 export will be calculated with the same percentage increase. In a few cases this leads to very high production increases if export has to be projected in line with the rest of final demand for this specific industry output. Some export-intensive industries have large stocks due to vulnerable exports. This can be the reason for the large changes in domestic final demand measured in relative terms and therefore the change in stocks is excluded from domestic final demand in (13).

[6] The imports not referable to a specific good are not included in this analysis.

[7] In general the subscript 0 corresponds to 1966 and subscript t corresponds to 1992.

[8] The production inputs associated with the production of domestic final demand are used in order to include the effect of changed production technology in the adjusted export. Export growth is assumed to be affected by the same production technology change as can be observed for domestic production technology including the imported inputs.

Industry	Energy input change (TJ) 27 industry level	Energy input change (TJ) 117 industry level	Energy consumption 1992 (TJ)	Energy intensity 1966 (TJ)/mill. DKK	Energy intensity 1992 (TJ)/mill. DKK
Agriculture etc.	-7147	-3692	41030	1.41	0.95
Forestry	-90	-88	151	0.10	0.20
Fishing	-505	-4075	11438	3.01	4.53
Mining	-4304	-2333	4546	1.91	0.25
Food, beverages and tobacco	-2426	1095	47208	0.72	0.59
Textiles	-91	-437	4489	0.82	0.43
Wood products, furniture	-3938	-3762	8487	1.16	0.75
Paper	-560	2562	11245	0.79	0.64
Chemical	-15333	-9719	27759	1.01	0.71
Non metallic minerals	-6319	-4588	23767	5.79	3.63
Basic metal industries	-2406	-2089	6640	4.95	2.34
Fabricated metal products	-3715	-2378	25487	0.73	0.39
Other manufacturing industry	-276	-306	1104	0.45	0.31
Electricity, gas and water	-280	-99	3529	0.21	0.20
Construction	-375	-108	17139	0.26	0.35
Wholesale and retail trade	-5969	-3633	41089	0.80	0.55
Restaurants and hotels	-263	-144	8408	0.83	0.68
Transport and storage	-29043	4254	79226	1.27	1.25
Communication	-216	-97	4303	0.83	0.38
Finance and insurance	-94	34	8250	0.29	0.55
Dwellings	0	0	1924	0.04	0.04
Business services	-1534	-993	12613	0.26	0.34
Private education and health	-16	-4	2907	0.52	0.46
Recreational and cultural service	-73	-66	1963	0.62	0.32
Household services	-534	-269	8799	0.90	0.54
Other service	0	0	388	0.04	0.12
Government services	18	118	51275	0.48	0.41
All Industries	-85489	-30819	455163	0.80	0.58
Manufacturing	-35064	-19623	156186	1.10	0.66

Table 4 Comparing the aggregation level effect on input-output calculation results

Table 4 shows the difference between the calculated and actual figures for 1992. Manufacturing energy consumption would have been 35064 TJ lower in 1992 if the trade patterns of 1966 had been kept constant.

The consequence of using different aggregation levels is striking. In the calculation based on the 117-industry disaggregation, energy demand is around 7% higher in 1992 than without the change in structure and balance of trade. For the calculation based on a 27 disaggregation level, the energy demand is found to be 19% higher in 1992. This is a result of very different energy intensities and different export/import developments among the subsectors belonging to a 27-level sector.

In Figure 4 the results from the calculation at the two aggregation levels are compared for some outstanding examples. The industries shown are those with the largest change in energy demand and some where the aggregation level has important implications. The industries with the highest negative figures in the graph above are those that have had the best relative export performance in the 1966 to 1992 period. If those industries had not been this successful in export markets their energy demand would have been up to 50% less. The best performers are the chemical industry, wood products and furniture, transport and agriculture. The chemical industry includes the successful medical industry, which is not energy intensive. Furniture has succeeded in export markets and the transport sector includes a large export component in the overseas fleet. The last industry with a good export performance is agriculture.

Government service has not been influenced by foreign trade changes as the import and export shares are still close to zero. For most of the other service industries that are not included in the graph the same applies. The one exception is the transport industry, which has a large and increasing share of international shipping. The only industry that would have had higher energy consumption without the foreign trade changes is textiles. This manufacturing industry has undergone a radical change of composition, with more and more of the processing being located outside Denmark, but with the design, administration and sales activities undertaken from Denmark.

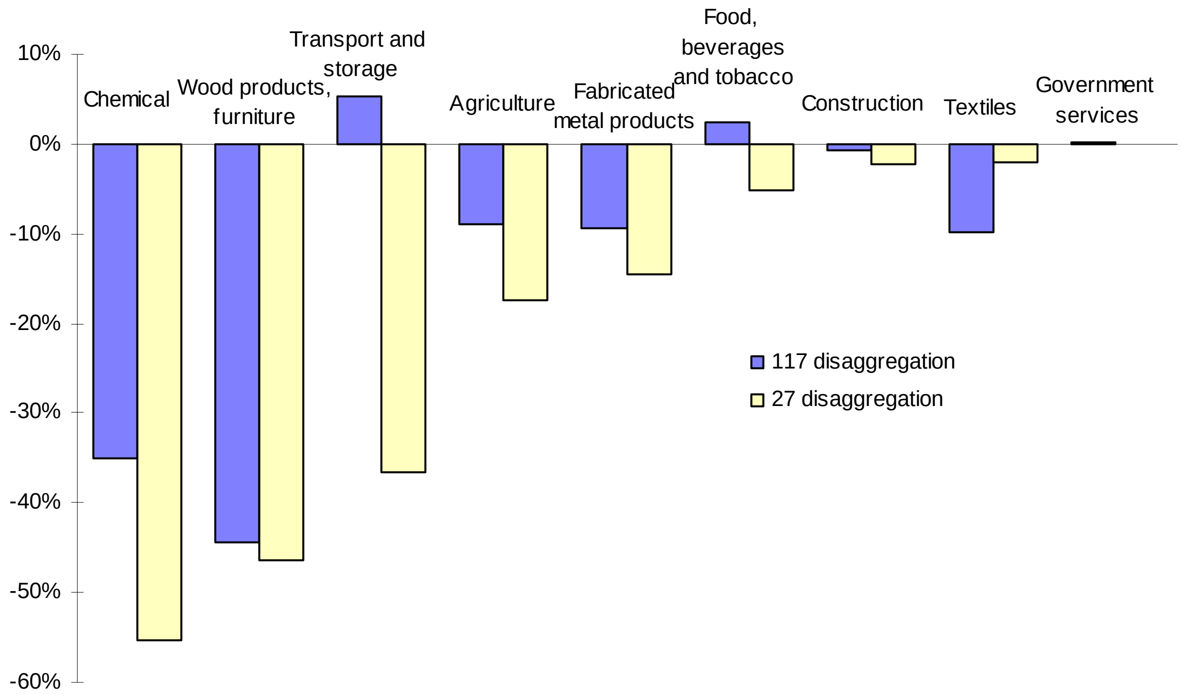

Figure 4 Energy demand in industry with constant export and import shares in final demand relative to actual energy demand in 1992

The importance of the level at which the calculations are conducted is evident from Figure 4. For most of the sectors included, there are large differences between the two calculations. Two of the sectors even have the opposite sign of the impact from trade patterns. Transport is the most striking example with a large difference in the level of the result and also in the sign of the effect. This is caused by the very different energy intensities among transport sectors and different developments of trade for the individual transport sectors.

The food, beverages and tobacco industries also have unequal signs in the two calculations of the trade effect. This is caused by a negative influence from export shares of processed cheese. As the energy intensity of cheese production exceeds the average for the sector, the 117 level calculation with unchanged trade patterns results in a higher energy consumption in 1992.

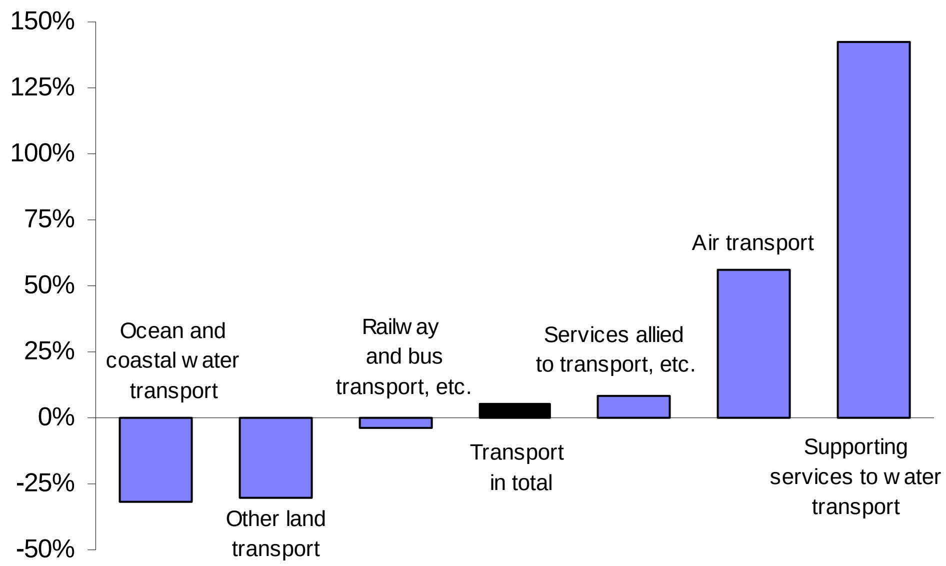

Figure 5 Disaggregation of the net trade effect for transport and storage

Air transport is the main reason there is a difference as this subsector has experienced a much more rapid growth in domestic final demand than exports. Thus, if export had grown as fast as domestic demand (domestic air traffic) the energy consumption for air transport would have been 14679 TJ higher in 1992 (58%). This is a result of the very high energy intensity of air transport, namely 4.52 TJ/mill. DKK, compared with only 0.27 TJ/mill. DKK for ocean and coastal transport. If the aggregate transport sector is used for the calculation, the development in ocean and coastal water transport production dominates the trade dependence. This subsector has considerably increased export earnings (production) also if examined as export shares. For this reason, the energy consumption in total transport is calculated as higher today relative to the consumption that would have existed without this change in trade patterns.

7. Conclusion

Trade patterns are important for analyses of changes in domestic energy consumption, especially in a small open economy as the Danish. Decomposition can be used as a way to analyse the impact of changing trade patterns for Denmark. Trade cannot be identified as a single component, but rather consists of three components embodied in the level of final demand, the input-output structure as well as the final demand for domestic production.

The conclusion of decomposition analyses of changes in energy consumption or emissions is that structural change in many cases, are of minor importance. In a broad interpretation change in trade patterns are also structural components, and because export is embodied in the level of final demand the relative importance of structural change might be more pronounced.

The decomposition of change in Danish energy consumption for 117 industries in six components finds trade to be relatively more important than other kinds of structural change if examined for aggregate figures or for manufacturing in total. For the entire period 1966 to 1992 the net effect of trade components has been to increase energy consumption by 11% for manufacturing. Increases in import shares in final demand and for intermediate inputs have reduced energy consumption, but this is outweighed by a large positive contribution from increasing export shares. If sectors at the 27-sector aggregation level are examined, the trade effect and effect of all other components varies very much. Within manufacturing the net trade effect varies from +58% in the chemicals sector to –33% in the paper sector.

The comparison of trade components and other components show that import shares for intermediate inputs (-13%) dominate the effect from the basic component of change in input-output structure (-3%). This means that much of the change in the inverted matrix for Danish production is caused by changes of import shares and not by a change in intermediate input technology. Another observation is that the change in import share for final demand has less impact on manufacturing energy consumption (-8%) than the change in import shares for intermediate inputs (-13%).

Among the manufacturing industries the three trade components have had different effects. Some industries have been especially influenced by increasing import shares in final demand (textiles), while others are influenced primarily by increased import shares for intermediate inputs (paper and basic metal industries). The chemicals sector has benefited from both a very high increase in export shares and at the same time no increase in import shares for final demand. The same applies to the wood products and furniture industry, where import shares have increased only slightly, while export shares have increased sharply.

The level of aggregation at which the calculations are conducted is important as there are important structural changes related to trade within the 27-industry aggregation. Two input-output calculations carried out at different aggregation levels illustrate this. The result of the two calculations ranges from 7% to 19% higher energy consumption for production today than would have been the case with unchanged trade patterns from 1966. For transport the aggregation level is especially important. This sector provides the main explanation for the difference between the 27-industry result of 19% higher energy demand today and the 7% result for calculations at the 117-industry level.

The main explanation for the positive contribution to energy consumption from trade patterns is the development in aggregate variables. Export has increased twice as much as import, which has resulted in production rising more than domestic final demand. The effect of strongly increasing export relative to imports in the period studied has resulted in the dominance of the export effect and consequently an increase in energy demand.

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APPENDIX A Decomposition results for 117 industries (All percentages indicate component contribution relative to base year energy consumption)

	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Total energy change TJ	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Sum of components	Net trade effect	Energy intensity 1992 TJ/mill. DKK
Agriculture	-3644	494	13133	-5083	-752	1332	5480	-14%	2%	52%	-20%	-3%	5%	22%	4%	0.83
Horticulture	-13255	-1126	4739	-2372	-787	4967	-7833	-81%	-7%	29%	-14%	-5%	30%	-48%	19%	2.40
Fur farsing,	-38	86	374	9	41	-224	248	-8%	19%	82%	2%	9%	-49%	54%	-21%	0.51
Agricultural services	-637	27	564	-121	-30	0	-198	-55%	2%	49%	-10%	-3%	0%	-17%	0%	1.06
Forestry and logging	70	1	-4	-54	9	67	89	112%	2%	-6%	-88%	15%	109%	143%	125%	0.20
Fishing	3537	-1951	1437	-1320	-396	3794	5101	56%	-31%	23%	-21%	-6%	60%	80%	23%	4.53
Extraction of coal, oil and gas	1073	670	148	2	195	50	2136									0.12
Other mining	658	44	473	-27	-100	68	1117	51%	3%	37%	-2%	-8%	5%	86%	1%	3.13
Slaughtering etc. of pigs and cattle	-1017	-193	3426	-589	-131	-1	1496	-22%	-4%	76%	-13%	-3%	0%	33%	-7%	0.20
Poultry killing, dressing, packing	-793	-43	1414	70	3	-522	130	-147%	-8%	262%	13%	1%	-97%	24%	-104%	0.33
Dairies	-2445	-109	1299	-561	-136	410	-1542	-38%	-2%	20%	-9%	-2%	6%	-24%	3%	0.42
Processed cheese, condensed milk	-657	-13	3206	153	33	-1973	748	-41%	-1%	202%	10%	2%	-124%	47%	-123%	0.81
Ice cream manufacturing	-427	-19	460	25	-6	284	317	-158%	-7%	170%	9%	-2%	105%	117%	96%	0.60
Processing of fruits and vegetables	192	-299	668	164	-80	81	726	53%	-83%	185%	45%	-22%	22%	201%	-82%	0.53
Processing of fish	146	-430	1111	146	-17	580	1536	40%	-119%	307%	40%	-5%	161%	425%	37%	0.33
Oil mills	-1506	-58	789	375	-721	396	-725	-70%	-3%	37%	17%	-33%	18%	-34%	-18%	0.78
Margarine manufacturing	-116	-37	-88	116	-69	138	-55	-27%	-8%	-20%	27%	-16%	32%	-13%	8%	0.55
Fish meal manufacturing	-1547	-166	3090	763	128	-329	1939	-133%	-14%	267%	66%	11%	-28%	167%	-32%	1.32
Grain mill products	-110	39	15	-108	-142	181	-124	-13%	5%	2%	-13%	-17%	22%	-15%	9%	0.67
Bread factories	-1	-27	21	93	-11	54	129	0%	-5%	4%	16%	-2%	9%	22%	3%	0.78
Cake factories	-582	-47	290	141	-7	464	259	-105%	-8%	52%	25%	-1%	83%	47%	74%	0.53
Bakeries	721	-2	-1335	-139	5	0	-750	28%	0%	-51%	-5%	0%	0%	-29%	0%	1.20
Sugar factories and refineries n.e.c.	136	-225	586	1010	-401	1376	2481	7%	-12%	30%	52%	-21%	71%	128%	39%	2.20
Chocolate and sugar confectonery	25	-133	503	31	-30	191	587	5%	-28%	105%	6%	-6%	40%	123%	6%	0.50
Manufacture of food products	-1244	-508	2433	397	-204	642	1517	-128%	-52%	251%	41%	-21%	66%	156%	-7%	0.99
Manufacture of prepared animal feeds	-443	-377	3833	845	2	-419	3441	-21%	-18%	184%	41%	0%	-20%	165%	-38%	2.61
Distilling and blending spirits	-2062	-141	565	-70	-264	262	-1710	-96%	-7%	26%	-3%	-12%	12%	-80%	-7%	1.35
Breweries	-467	85	2629	340	10	158	2753	-13%	2%	73%	9%	0%	4%	76%	7%	1.39
Tobacco manufactures	-205	22	-179	-30	1	150	-240	-33%	4%	-29%	-5%	0%	24%	-39%	28%	0.38
Spinning, weaving etc. textiles	-1840	-821	705	-559	-817	1608	-1725	-42%	-19%	16%	-13%	-19%	37%	-40%	-1%	1.12
Manufacture of made-up textile goods	-17	-35	196	56	-33	58	224	-18%	-37%	206%	59%	-35%	61%	236%	-11%	0.28
Knitting mills	-605	-250	316	22	-19	186	-350	-91%	-37%	47%	3%	-3%	28%	-52%	-12%	0.16
Cordage, rope and twine industries	-211	-61	109	-106	-92	114	-247	-39%	-11%	20%	-19%	-17%	21%	-45%	-7%	0.58
Manufacture of wearing apparel	-610	-567	197	-59	-58	381	-716	-49%	-45%	16%	-5%	-5%	30%	-57%	-19%	0.17
Manufacture of leather products	-42	-235	109	-130	-63	64	-297	-8%	-45%	21%	-25%	-12%	12%	-57%	-45%	0.85
Manufacture of footwear	-183	-151	79	37	-20	44	-194	-53%	-44%	23%	11%	-6%	13%	-56%	-36%	0.19
Manufacture of wood products, ex. furniture	-3541	-235	1693	-51	10	1736	-388	-66%	-4%	31%	-1%	0%	32%	-7%	28%	0.98
Manufacture. of wooden furniture, etc.	171	-133	-226	-66	-12	2051	1785	10%	-8%	-13%	-4%	-1%	121%	105%	112%	0.56
Manufacture. of pulp, paper, paperboard	-264	-633	2919	475	-4082	1882	297	-6%	-13%	62%	10%	-87%	40%	6%	-60%	5.30

	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Total energy change TJ	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Sum of components	Net trade effect	Energy intensity 1992 TJ/mill. DKK
Manufacture of paper containers, wallpaper	-1517	-237	1496	519	-522	624	362	-79%	-12%	78%	27%	-27%	33%	19%	-7%	0.53
Reproducing and composing services	-126	-8	95	157	0	14	133	-106%	-6%	80%	132%	0%	12%	112%	6%	0.23
Book printing	375	-45	508	-381	-162	135	430	51%	-6%	69%	-52%	-22%	18%	58%	-10%	0.54
Offset printing	57	-35	389	197	-42	51	617	16%	-10%	109%	55%	-12%	14%	173%	-7%	0.47
Other printing	-522	-11	171	334	-81	95	-13	-157%	-3%	52%	101%	-25%	29%	-4%	1%	0.29
Bookbinding	93	-8	50	2	-21	14	130	148%	-13%	79%	4%	-33%	22%	207%	-24%	0.44
Newspaper printing and publishing	-3	-5	214	-250	-12	0	-56	0%	-1%	30%	-34%	-2%	0%	-8%	-2%	0.23
Book and art publishing	-48	0	-74	11	0	0	-112	-19%	0%	-30%	4%	0%	0%	-45%	0%	0.24
Magazine publishing	-12	-1	10	-20	0	0	-24	-10%	-1%	8%	-17%	0%	0%	-20%	-1%	0.13
Other publishing	-12	-3	80	30	-1	0	93	-15%	-4%	100%	38%	-2%	0%	117%	-6%	0.13
Manuf. of basic industrial chemicals	-1956	207	3618	123	490	3262	5744	-104%	11%	192%	7%	26%	173%	305%	210%	1.71
Manuf. of fertilisers and pesticides	-1875	114	1145	-1157	-759	1049	-1484	-62%	4%	38%	-38%	-25%	34%	-49%	13%	1.75
Manuf. of basic plastic materials	-6194	-82	3312	2382	-1128	2282	573	-290%	-4%	155%	112%	-53%	107%	27%	50%	0.68
Manuf. or paints and varnishes	-44	-24	154	-59	-172	180	35	-9%	-5%	31%	-12%	-35%	37%	7%	-3%	0.50
Manufacture of drugs and medicines	-419	-61	2068	172	-81	1406	3084	-67%	-10%	330%	27%	-13%	224%	492%	202%	0.66
Manufacture of soap and cosmetics	-396	-183	265	-22	-21	210	-146	-71%	-33%	48%	-4%	-4%	38%	-26%	1%	0.33
Manuf. of chemical products n.e.c.	-998	-97	368	320	-177	138	-446	-124%	-12%	46%	40%	-22%	17%	-55%	-17%	0.35
Petroleum refineries	-476	366	396	-1178	716	942	766	-26%	20%	22%	-64%	39%	51%	42%	110%	0.19
Manufacture of asphalt and roofing cater	64	-136	675	306	-345	488	1053	3%	-7%	36%	16%	-18%	26%	56%	0%	2.33
Tyre and tube industries	-207	12	145	-14	-58	73	-49	-66%	4%	46%	-4%	-19%	23%	-15%	9%	1.13
Manuf. of rubber products n.e.c.	-460	-185	301	-81	-511	639	-297	-42%	-17%	28%	-8%	-47%	59%	-27%	-5%	1.31
Manuf. of plastic products n.e.c.	45	-106	1893	841	-86	707	3294	5%	-11%	195%	87%	-9%	73%	340%	53%	0.85
Manuf. of earthenware and pottery	-499	-285	-416	-26	-45	276	-995	-40%	-23%	-33%	-2%	-4%	22%	-79%	-4%	1.10
Manuf. of glass and glass products	-7136	-562	1503	-658	700	1376	-4777	-116%	-9%	24%	-11%	11%	22%	-78%	25%	1.63
Manuf. of structural clay products	-188	-32	-1199	-3310	-740	1982	-3486	-3%	-1%	-19%	-54%	-12%	32%	-57%	20%	6.50
Manuf. of cement, lime and plaster	-2194	-311	2218	-3034	-2526	3410	-2436	-15%	-2%	15%	-21%	-17%	23%	-17%	4%	14.20
Concrete products and stone cutting	1532	-44	281	-343	-91	583	1917	97%	-3%	18%	-22%	-6%	37%	121%	28%	1.29
Non-metallic mineral products n.e.c.	-3727	-91	1029	-554	215	1936	-1191	-74%	-2%	21%	-11%	4%	39%	-24%	41%	2.55
Iron and steel works	-8332	-150	1806	-1769	-2499	5153	-5790	-83%	-1%	18%	-18%	-25%	51%	-57%	25%	3.10
Iron and steel casting	-164	-153	540	-550	-234	625	64	-11%	-10%	35%	-36%	-15%	41%	4%	16%	2.42
Non-ferrous metal works	-290	48	-89	-289	-578	525	-672	-30%	5%	-9%	-30%	-59%	54%	-69%	0%	0.72
Non-ferrous metal casting	-41	-34	199	-126	55	120	173	-14%	-12%	69%	-44%	19%	42%	60%	49%	1.23
Manufacture of metal furniture	-402	-63	695	123	-36	246	563	-111%	-17%	192%	34%	-10%	68%	156%	41%	0.62
Manuf. of structural metal products	-3406	-124	1810	1555	-339	1180	677	-153%	-6%	81%	70%	-15%	53%	30%	32%	0.43
Manuf. of metal cans and containers	-746	-73	661	179	-470	266	-185	-83%	-8%	74%	20%	-52%	30%	-21%	-31%	0.40
Manuf. of other fabricated metal products	-1623	-407	1857	-113	-71	597	240	-49%	-12%	57%	-3%	-2%	18%	7%	4%	0.60
Manuf. of agricultural machinery	-324	-170	217	37	-40	176	-103	-35%	-18%	23%	4%	-4%	19%	-11%	-4%	0.47
Manufacture of industrial machinery	-458	35	658	-78	-83	389	462	-31%	2%	44%	-5%	-6%	26%	31%	23%	0.40
Repair of machinery	-832	13	986	-677	-60	0	-569	-47%	1%	56%	-38%	-3%	0%	-32%	-3%	0.50
Manufacture of household machinery	-125	-41	310	-11	-31	369	471	-51%	-16%	125%	-4%	-13%	149%	190%	120%	0.35

	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Total energy change TJ	Intensity component	Import share component	Level component	Input-output structure	IO-import share	Export share component	Sum of components	Net trade effect	Energy intensity 1992 TJ/mill. DKK
Manuf. of refrigerators, accessories	-3385	-1020	4555	833	-872	1354	1466	-99%	-30%	133%	24%	-25%	40%	43%	-16%	0.38
Manuf. of telecommunication equipm.	-1918	-401	2079	465	-194	433	464	-264%	-55%	286%	64%	-27%	60%	64%	-22%	0.22
Manuf. of electrical home appliances	-119	-69	77	34	-9	31	-55	-49%	-29%	32%	14%	-4%	13%	-23%	-19%	0.45
Manuf. of accumulators and batteries	24	-61	15	-22	-83	32	-96	12%	-30%	7%	-11%	-41%	16%	-47%	-56%	0.76
Manuf. of other electrical supplies	-1808	-100	1054	-195	-507	527	-1031	-69%	-4%	40%	-7%	-19%	20%	-39%	-3%	0.32
Ship building and repairing	-926	55	-206	-656	135	1180	-417	-33%	2%	-7%	-23%	5%	42%	-15%	49%	0.36
Railroad and automobile equipment	-377	-560	485	-70	8	374	-141	-32%	-47%	41%	-6%	1%	31%	-12%	-15%	0.41
Manufacture of cycles, mopeds, etc.	-360	-280	495	-37	-31	106	-106	-75%	-59%	104%	-8%	-6%	22%	-22%	-43%	0.63
Professional and measuring equipment	51	-133	663	56	-18	183	801	32%	-85%	423%	36%	-11%	117%	511%	20%	0.23
Manufacture of jewellery, etc.	3	-60	-73	-3	-3	1	-134	2%	-31%	-37%	-2%	-1%	0%	-69%	-32%	0.16
Manuf. of toys, sporting goods, etc.	-1031	-113	777	29	-71	661	253	-130%	-14%	98%	4%	-9%	84%	32%	60%	0.33
Electric light and power	239	-17	145	54	-16	4	408	1143%	-83%	692%	257%	-75%	17%	1951%	-141%	0.05
Gas manufacture and distribution	-7	9	22	12	3	-1	38	-53%	69%	169%	98%	25%	-11%	297%	82%	0.02
Steam and hot water supply	14	0	18	1	0	0	33	198%	-2%	252%	16%	-1%	0%	464%	-3%	0.01
Water works and supply	1494	-51	595	-175	-24	0	1838	128%	-4%	51%	-15%	-2%	0%	157%	-6%	4.96
Construction	4500	-36	1641	-2181	-43	0	3881	34%	0%	12%	-16%	0%	0%	29%	-1%	0.35
Wholesale trade	-9222	-448	8487	640	-454	3105	2107	-61%	-3%	56%	4%	-3%	20%	14%	15%	0.36
Retail trade	-4181	40	8808	346	-24	0	4989	-22%	0%	47%	2%	0%	0%	27%	0%	0.87
Restaurants and hotels	-1486	-43	4085	-173	-18	102	2468	-25%	-1%	69%	-3%	0%	2%	42%	1%	0.68
Railway and bus transport, etc.	4741	-116	4067	-3592	-99	-49	4953	51%	-1%	43%	-38%	-1%	-1%	53%	-3%	3.98
Other land transport	10625	-456	6218	-7706	-308	5814	14187	85%	-4%	50%	-62%	-2%	46%	113%	40%	1.90
Ocean and coastal water transport	-4673	16	4355	331	8	2667	2704	-98%	0%	91%	7%	0%	56%	56%	56%	0.27
Supporting services to water transport	-13	-3	183	-19	-3	-116	28	-13%	-3%	186%	-20%	-3%	-118%	29%	-124%	0.13
Air transport	-4811	-122	24113	5572	-65	-9455	15234	-43%	-1%	218%	50%	-1%	-85%	138%	-87%	4.52
Services allied to transport, etc.	505	-129	1831	1131	-69	-200	3068	42%	-11%	154%	95%	-6%	-17%	258%	-34%	0.37
Communication	-3220	-51	3487	1576	-22	0	1769	-127%	-2%	138%	62%	-1%	0%	70%	-3%	0.38
Financial institutions	2477	-14	1966	296	-5	0	4719	137%	-1%	109%	16%	0%	0%	261%	-1%	0.52
Insurance	964	-4	343	-337	-5	-126	834	108%	0%	38%	-38%	-1%	-14%	93%	-15%	0.74
Dwellings	270	0	928	0	0	0	1198	37%	0%	128%	0%	0%	0%	165%	0%	0.04
Business services	1942	-194	4090	3752	-85	233	9738	68%	-7%	142%	131%	-3%	8%	339%	-2%	0.34
Education, market services	-87	-1	13	7	-1	0	-70	-37%	0%	6%	3%	0%	0%	-30%	-1%	0.33
Health, market services	-256	3	1378	-272	-4	0	849	-14%	0%	73%	-14%	0%	0%	45%	0%	0.47
Recreational and cultural services	-1295	-14	1496	186	94	-53	414	-84%	-1%	97%	12%	6%	-3%	27%	2%	0.32
Repair of motor vehicles	-293	-29	1544	-157	-21	0	1045	-14%	-1%	75%	-8%	-1%	0%	51%	-2%	0.35
Household services	-3920	-58	869	466	-26	0	-2669	-47%	-1%	10%	6%	0%	0%	-32%	-1%	0.75
Domestic services	0	0	0	0	0	0	0							0%	0%	0.00
Private non-profit institutions	-114	0	370	0	0	0	256	-86%	0%	280%	0%	0%	0%	194%	0%	0.14
Producers of government services	-5902	-27	30428	1499	-11	-123	25865	-23%	0%	120%	6%	0%	0%	102%	-1%	0.41
Total	-96919	-15012	203442	-11896	-21735	58498	116378	-29%	-4%	60%	-4%	-6%	17%	34%	6%	0.58
Manufacturing	-72974	-11511	71099	-4186	-18718	46645	10355	-50%	-8%	49%	-3%	-13%	32%	7%	11%	0.66

Model description and critical assessment of results

Henrik Klinge Jacobsen

1. Introduction

This paper contains documentation for the Hybris model and a critical assessment of the model and the results obtained in the first five papers in this dissertation. The first two papers include examples of describing technological change taken from ADAM and Hybris. The next three papers are analyses based on the use of Hybris with modifications necessary to analyse the three different topics covered by the papers. The documentation and description of the model is basically taken from the publication Klinge Jacobsen et. al. (1996). Additional comments have been added at some places where new insight was obtained by using the model and implementing changes in the first five papers. The multiplicators, sensitivity analysis and model critique was not included in the 1996 report.

2. The HYBRIS model - overview

The integration of two different kinds of models was the main objective for the construction of Hybris. Based on experience with energy simulation models for Denmark some areas of energy supply and demand were chosen as suitable to link to the macroeconomic model ADAM of Statistics Denmark. A new model covering supply of electricity, heat and natural gas was developed. This model includes many bottom-up characteristics as a lot of detail, projected efficiencies, policy driven capacity expansion, regulated pricing, but also economic behaviour driving the demand for fuels in large CHP plants. The model developed for residential electricity demand is a vintage model of electric appliances with bottom-up characteristics and linked to economic drivers. However, this model has little price response and it is without any behaviour regarding the consumer choice between different types and versions of appliances. The model of residential heat demand is a bottom-up model covering local heating technologies in the residential sector.

Technical bottom-up models are characterised by a lot of detail, focus on projected technological progress, physical restrictions regarding networks, capital stock etc. These models include little description of behaviour, prices play a minor role and interactions between economic conditions and final demand are treated in an ad. hoc. manner.

ADAM is a macroeconometric model of Denmark developed during the last 30 years. The characteristics of the model with regard to energy is a fairly detailed description of energy as a specific input to production, but still it is not designed to cover energy sector issues in general. There is no documentation of ADAM in here except for the relations where the linking enters directly. Documentation of the ADAM version used for the linking[1] can be found in Danish in Danmarks Statistik (1996) and for the equation system and variable list in English in Danmarks Statistik (1998).

The two types of models are integrated by linking the energy models to ADAM in an iterative procedure. Integration of these two different types of models raises both theoretical problems regarding the behaviour of agents in different contexts as well as practical problems for implementation. The integration implies that households react to electricity price changes by adjusting intensity of use for a given appliance but they don't react by buying more efficient versions of appliances. This inconsistency has been accepted, but on the other hand the integration in Hybris has been limited to areas where such inconsistencies are of limited importance. With a macroeconometric model like ADAM there will be other inconsistencies. In ADAM, for example, household demand for gasoline is found dependent on gasoline prices, whereas demand for public transport is found independent of the price for public transport.

The model properties that are a result of linking the two types of models are important for analysis of energy issues, but energy is not so important that basis properties of the macroeconomic model have been affected. The most important interaction derives from the determination of fuels used for electricity and heat production including the implication for output prices and to the corresponding demand reaction in the macroeconomic determined electricity and heat demand. This link is necessary to conduct analyses where bottom-up measures are combined with taxes, but also if the analyses should include any assessment of economic costs of emission reduction policies.

3. Energy supply module

This section serves as documentation for the energy supply module (electricity, heat and natural gas retail distribution). The main focus is on electricity and heat production.

The model is a bottom-up description of specific technologies and specific plants. Prices are very important as a large share of electricity is produced on large plants where joint production costs of electricity and heat are minimised. Special attention has also been placed on the regulated price setting.

The energy supply module in Hybris is a vintage model with technical characteristics for each category and vintage of power production capacity. Long-term technology choices are seen mainly as restricted by public regulation. Short-term production decisions are unregulated. The model includes four categories of producers: major combined heat and power plants, secondary combined heat and power plants, wind power and district heating producers. The largest part of production takes place at major power plants. Fuel input in electricity and heat production by major plants is found by minimising total fuel cost for electricity and heat generation by the major power plants of Denmark, which are primarily combined heat and power plants.

3.1 Inputs and sectoral description

The model of electricity and heat production takes final demand for electricity, heat and natural gas as given from ADAM. The fixed price demands from ADAM are converted to

[1] A more general introduction to an older version of ADAM can be found in Dam (1986)

energy terms and these demand variables along with series for prices, wages etc. are transferred as input to the model of electricity and heat production.

A lot of exogenous variables in the model as listed in the appendix have to be projected. These variables are technical parameters, fuel prices, sector specific investments and regulated capacity expansion.

The model consists of three sectors.

- Electricity
- Heat
- Natural gas distribution.

The electricity sector produces both electricity and heat, whereas the heat sector only produces heat (district heat). The description of natural gas retail distribution is very rudimentary.

The electricity sector is divided into a number of categories

- Public utilities.
    - Large plants dominated by CHP plants
    - Wind turbines
    - Decentral CHP
    - Miscellaneous, including hydro
- Non-utility.
    - Wind turbines
    - Decentral CHP
    - Industrial cogeneration
    - Miscellaneous, including mini CHP

These categories have very diverging characteristics with respect to the conditions under which they operate. As a consequence of this the modelling of the production choices and fuel choices also varies between categories. The most important group of producers is large CHP plants. This group of plants are important based on their large share of electricity production, but also because the production flexibility of these plants is large with regard to output mix, level of operation and fuel mix.

Fuels and fuel prices

Basically four fuels and four fuel prices are represented in the energy model[2]:

- coal
- fuel oil
- natural gas
- biomass

The price series are taken from energy matrices for Denmark until 1991 and projected following Danish Energy Agency projections. The price of biomass is constructed and

[2] Additional fuels can very easily be incorporated, for example, other oil products or a different type of biomass.

forecast by Danish Energy Agency projections, but at a higher price level as base year actual prices for straw have been used.

One objective of linking energy models and ADAM is to use consistent assumptions also for prices. Therefore the ADAM prices crude oil (*pm3r*), coal (*pm3k)* and imported refined products (*pm3q*) are also projected in the energy model.

3.2 Expansion of electricity producing capacity

Production capacity for electricity is determined based on projected demand developments. Domestic demand is the dimensioning variable and the total capacity is planned to exceed the projected maximal load (peak demand) by some reserve.

The different production categories are treated differently. All secondary categories are projected exogenously as determined by public policy, agreements etc. The capacity of central plants is then planned to cover the rest of capacity to meet total capacity targets.

The input variable *bjeldk* constructed from ADAM fixed price energy demands and input-output coefficients is treated as domestic electricity demand. The size of capacity is determined for electricity as a whole with a reserve capacity of 20% relative to peak load. The load duration curve for domestic demand is assumed to be constant in time in the sense that peak demand is increasing at the same rate as total domestic demand. This need not be the case as the time pattern of consumption might change, for example, as a consequence of increased use of time differentiated tariffs. The load duration curve of 1992 is used for determining the peak load corresponding to the demand developments determined in ADAM.

The data for central plants are based on planning publications from ELSAM and ELKRAFT. For the existing capacity (1992) the planned scrapping of plants is known and the remaining capacity at a given future year is thus known. This remaining capacity variable called the "deathcurve" is used when calculating the necessary capacity expansion to meet the 20% reserve constraint.

The necessary expansion is calculated as the difference between warranted capacity and the projected capacity of central plants (death-curve) combined with projected secondary capacity. The secondary capacity projections are treated in detail below.

The maximum capacity of each plant for electricity production is used on both central and decentral CHP. This means that no constraints for heat deliverances are binding. No heat production from central CHP takes place at the time of peak electricity demand. Heat storage within 24 hours is assumed possible. The maximum production of decentral CHP is also assumed regardless of the local demand for heat.

The reserve restriction has to be satisfied for all years in the planning. As building time for large power plants is around five years the erection of plants has to be initiated five years ahead of the first year of operation.

The warranted power capacity is defined as

$$K^{Ø} = K^{S} + K^{0} + K^{Ny} \qquad (1)$$

The warranted capacity has to be met in the planning and consists of three elements: K^S is the total projected secondary capacity, K^0 is the initial (1992) central capacity reduced for the plants scrapped since then, and K^{Ny} is the accumulated capacity built since the initial year. This last element is the one that responds to changes in final electricity demand.

Central capacity is expanded in discrete steps in the way that the size of plants is exogenous (usually a value between 100 and 400 MW is assumed[3]). This property is reflected in both efficiency developments, fuel substitution options etc.[4] For investment and price setting the dependence is less because the building of plants is distributed on a time period.

The expansion calculation is not related to the technology choice of the new large plants. This aspect is handled in connection with the fuel calculations. There are five different types of technology. For each of the possible new plants (up to 75 can be added) one of these technologies is chosen exogenously. The technical parameters for each of the five technologies change over time and the endogenous expansion of production capacity results in large plants acquiring the technical parameters that are determined by the year they are built. The parameters for C_v, C_m and fuel efficiency are projected exogenously for each of the five technologies.

Calculations for capacity expansion cover the period 1994-2022 and the following five years. The extra five years are needed to generate investments for the years 2018-2022 that depend on expansion in the following five years. These investments influence electricity prices in 2018-2022.

Exogenous capacity categories

The seven secondary categories are all projected exogenously. It is relevant to have the categories independently projected both as a consequence of different owner structures and production properties. Projections will differ among the owner groups because some are directly regulated in agreements between authorities and utilities and other are regulated by investment subsidies or subsidies to production. In general the categories are projected as net expansion as the replacement will be more continual and the initial situation (1992) is only a minor capacity in these seven categories.

The maximum power capacity of all categories is included in total power capacity and expansion, except for wind power that is adjusted by a capacity value. Wind turbines are projected by expansion per year. The non-utility expansion is regulated differently from the utility owned expansion because the future utility expansion will be windparks (probably offshore) that are treated in direct agreements and the non-utility expansion will be replacement with larger wind-turbines and expansion regulated by subsidies to production.

The capacity value of wind is less than one because availability is insecure. The parameter is exogenous and normally set to 0.25 so that 25% of wind turbine capacity is included in the expansion calculations. This parameter will depend on the share of wind power in total production and the extent to which import is available. There are no vintage specific technological data for wind power. The average production of utility and non-utility windpower differ in the historical material and this parameter (that might reflect different average size or location of wind turbines) is also projected differently which is another reason for treating wind turbines in two categories.

Decentral CHP is projected as vintages with specific technology parameters for each year. Also here there can be large differences between owner categories with respect to the

[3] For the analyses presented in the other papers the expansion size is 400 MW

[4] The discrete expansion can on some occasions result in inability to solve the iteration between the energy module and ADAM as rising demand creates the need for an extra plant which raise electricity price and reduce final electricity demand and finally the plant will not be needed anyway. The economic implication of this on and of plant is however only marginal.

regulation and the dependence on emerging district heat markets. In addition the fuel mix for utility and non-utility CHP might be quite different. This is the reason for the independent projection of utility and non-utility CHP expansion. Expansion is seen as net and no account is taken of vintage effects on average stock parameters for decentral CHP. Initially this production category is relatively small and the physical lifetime of facilities will be close to the lifetime of large plants. Data is taken from DEF annual statistics and from Danish Energy Agency energy statistics. Projections are based on ELSAM/ELKRAFT planning publications.

The vintage specific technology data for non-utility expansion are identical for decentral CHP and industrial cogeneration except that it is only the electricity part of cogeneration that is included in the model. Vintage specific data for utilities decentral CHP are given only for CHP as miscellaneous mainly covers hydro and only account for a marginal production.

3.3 Electricity production at secondary facilities

The seven different secondary categories are all exogenously projected with regard to production capacity and technical parameters as described in the section about capacity expansion. Electricity production is calculated based on the capacity for seven categories and technical parameters for each vintage of most of these categories. Production on secondary units is independent of demand for various reasons. Wind turbines are operating independent of demand and as long as production from this source is not exceeding domestic demand and foreign transmission capacities this production will be used. Production is depending on location and efficiency of wind turbines. This is reflected in a projection of average operating hours per year. Production from both utility and non-utility CHP is assumed to be a by-product of the heat that is demanded by the local heat market. They have to meet the local heat demand and it is assumed that no electricity is produced at times with no heat demand. This means that production is projected by average operation time based on the characteristics of historical observations. As for heat it is assumed that decentrally produced electricity constitutes a minor share of total electricity production. Industrial co-generation production is assumed to be determined by the joint product (process heat etc.) and hereby assumed independent of electricity demand and prices. This assumption can be questioned as some of the facilities in Denmark have been dimensioned not only for the locally demanded process heat but just as well for electricity production.

Production from the miscellaneous category is for utility owned treated as hydropower projected by a constant operating time. For miscellaneous non-utility the calculation assumes micro scale CHP, which is and probably will be of a marginal importance for production.

Electricity production from secondary categories is aggregated and the final demand from ADAM is reduced by this production to find the demand to be delivered from central plants. It is assumed that the secondary production has the same time distribution as final demand, which implies that the load duration curve for large plants corresponds to the duration curve of final demand.

As operating time for secondary capacity is less than the average for large plants there could in principle be situations where the reserve restriction (20%) is incapable of securing the production demanded at peak times. The production of secondary categories will be underestimated at such peak load situations as these will be associated with winter times and heat demand. This problem will only arise if secondary production constitute a major share of total production.

3.4 Large producers minimise joint costs. (heat and electricity)

The category large power plants comprises around 50 Danish plants (1992). A major part of electricity production from these plants comes from combined heat and power plants (CHP). These plants are characterised by joint production and to some extent flexibility between output mix for the two products electricity and heat.

The large plants are modelled with individual plant characteristics. Their production is given from total demand reduced by the production that comes from secondary categories. As a whole these plants have to fulfil the electricity and heat demands. The main assumption is now that a central planning authority assures that demand is met and that output levels and mix for each plant are determined so that the joint costs for heat and electricity production from all the large plants are minimised.

For each plant the cost minimising fuel mix is found under the assumption that output mix is independent of fuel mix.

In minimising production cost substitution between fuels is allowed within the technical constraints specified for each plant.

Given the cost minimising fuel mix on each plant they are sorted according to marginal costs. Thus substitution between plants with differing production costs takes place within the bounds given by the duration curve. Plants with high marginal costs (fuel costs) will have short producing times, but as long as the peak demand includes the capacity they will produce.

As the production frontier of each plant is constrained by linear restrictions the calculations for the centrally planned operation of large power plants in Denmark is characterised as a linear optimisation problem. The dual problem to the minimisation problem of fuel costs is maximising revenues, which is done at the decentral level. For each plant the production is found by maximising the revenue based on shadow prices for heat and power. By running two iteration procedures the required electricity and heat production is distributed on individual plants. First, electricity production is distributed according to the marginal production cost given the shadow price of heat. At the upper iteration level the shadow price of heat is adjusted to reach the required heat production. In this way, the combined production cost of heat and power is minimised for the large power plants.

Fuel use for the production of power and heat is found by

$$E = \sum_{i=1}^{n} \frac{\left(P_i + Q_i\right)}{\eta_i(f_i)} \qquad (2)$$

P_i Electricity production at plant i
Q_i Heat production at plant i
f_i Fuel mix at plant i
η_i Fuel efficiency at plant i,

$P_i + Q_i$ is found by specifying full load hours for each plant exogenously[5] or by the production that results from sorting the plants by the marginal production cost of electricity and setting their production according to their position along the duration curve until the plants necessary to meet the total electricity demand are put into operation. Production of electricity and heat, as well as fuel demand for each plant is found based on a duration curve for electricity demand. This duration curve is based on the assumption of 365 identical 24-hour periods, and the use of a linear approximation. Heat is assumed to be storable to the extent necessary within the 24-hour period and no duration curve is applied for heat.

Electricity production $P_D(t)$ has to meet demand at any given time during the 24-hour period, as there is no storage capabilities:

$$P(t) = P_D(t),\ t \in \left[0, \bar{t}\right], \tag{3}$$

$P(t)$ is the total central capacity (in MW) at time t, and $\bar{t}$ is the 24-hour period. The production of heat is assumed to be storable within the 24-hour period so that production can be planned for any period within the 24 hours:

$$\int_0^{\bar{t}} Q(t)\, dt = H, \tag{4}$$

$Q(t)$ is the central heat capacity at time t (in MJ/s) and H is the heat demand for the period (in MWh).

The shadow price of electricity production $p_e(t)$ will fluctuate during the 24 hours. For heat production the shadowprice p_h will be the same for the whole 24-hour period.

Three different types of central plants exist: condensing, back-pressure and condensing extraction. The technical characteristics of these plants influence the marginal production costs of the plants.

Condensing plant

A condensing plant produces only electricity. Marginal profit based on the shadow price of electricity is $\Pi(t)$ at time t:

$$\Pi(t) = p_e(t)\, P(t) - \frac{p_F}{\eta} P(t), \tag{5}$$

s.t $\quad 0 \le P(t) \le Pmax$

$P(t)$ is the capacity of the condensing plants at time t, η is fuel efficiency and p_F is the fuel price. The plant will produce at max capacity for shadow prices above marginal production

[5] There is an option in the model to exogenously specify production for each major plant, but the default is the endogenous production determination for each plant.

cost. Maximising contribution margin results in the following production for shadow prices $p_e(t)$:

$$P(t) = \begin{cases} 0 & for \;\; p_e(t) < MC_k \\ [0, P_{\max}] & for \;\; p_e(t) = MC_k \\ P_{\max} & for \;\; p_e(t) > MC_k \end{cases} \tag{6}$$

P_{max} is the max capacity of the plant, and:

$$MC_k = \frac{p_F}{\eta} \tag{7}$$

$MC_k = p_F / \eta$ is the marginal production cost of the condensing plant. A given condensing plant will produce if its marginal production cost is below the shadow price. The condensing plants of Denmark are mainly old low efficiency fuel oil based plants and they only produce at peak demand, especially when export demand is high.

Back-pressure plant

A back-pressure plant produces electricity in a fixed output mix. This category of plants is described from its maximisation of profit contribution:

$$\begin{aligned} &Max\ \Pi(t) = p_e(t)P(t) + p_h\, Q(t) - \frac{p_F}{\eta}(P(t)+Q(t)) \\ &s.t. \;\; (i) \qquad Q(t) \le Q_{\max}, \\ &\qquad\; (ii) \qquad P(t) = c_m\, Q(t), \end{aligned}$$

η is total fuel efficiency, Q_{max} is the maximum heat production per unit of time and c_m is the output mix ratio (electricity per heat). This results in the following output decisions:

$$\begin{aligned} &Q(t) = \begin{cases} 0 & for \;\; p_e(t) < MC_m \\ [0, Q_{\max}] & for \;\; p_e(t) = MC_m \\ Q_{\max} & for \; p_e(t) < MC_m \end{cases} \\ &P(t) = c_m\, Q(t), \end{aligned} \tag{8}$$

where,

$$MC_m = -\frac{p_h}{c_m} + \frac{p_F}{\eta}\frac{c_m + 1}{c_m}. \tag{9}$$

Extraction condensing

For an extraction condensing plant fuel consumption F is given by:

$$F = \frac{1}{\eta}(P + c_v Q). \quad (10)$$

Fuel consumption is constant for any output mix on the line that has slope $-c_v$. in the (Q,P) space.

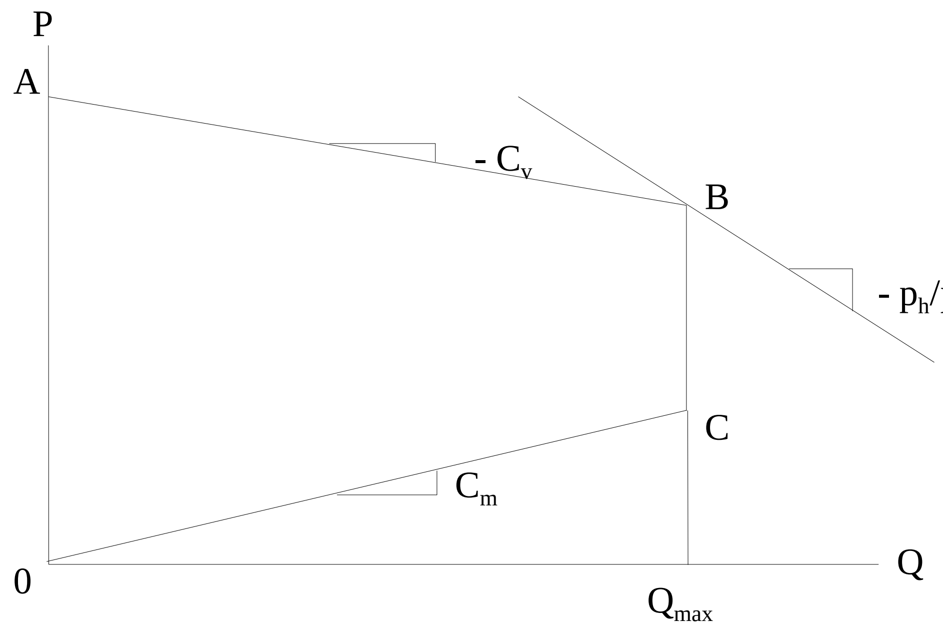

Figure 1. Production possibilities for an extraction condensing plant.

The contribution margin of an extraction condensing plant can be stated as:

$$\Pi(t) = (p_e(t) - \frac{p_F}{\eta})P(t) + (p_h - c_v\frac{p_F}{\eta})Q(t). \quad (11)$$

This implies that:

$$p_e(t) < \frac{p_F}{\eta} \;\; og \;\; p_h < c_v\frac{p_F}{\eta} \;\Rightarrow\; (P(t), Q(t)) = (0,0) \quad (12)$$

and

$$p_e(t) > \frac{p_F}{\eta} \;\; og \;\; p_h < c_v\frac{p_F}{\eta} \;\Rightarrow\; (P(t), Q(t)) = (\eta F_{max}, 0) \quad (13)$$

For $p_e(t) > p_F/\eta$ *and* $p_h > c_v\, p_F/\eta$ the optimal choice will be maximum operation on the c_v-line (AB in Figure 1) with an output mix depending on relative shadow prices p_h/p_e:

For $p_e(t) > \frac{p_F}{\eta}$ *and* $p_h < c_v \frac{p_F}{\eta}$. output will be:

$$Q(t) = \begin{cases} 0 & for \ \frac{p_h}{p_e(t)} < c_v \\ [0, Q_{\max}] & for \ \frac{p_h}{p_e(t)} = c_v \\ Q_{\max} & for \ \frac{p_h}{p_e(t)} > c_v \end{cases} \tag{14}$$

$$P(t) = -c_v\, Q(t) + \eta F_{\max}$$

For $p_e(t) < p_F/\eta$ *and* $p_h > c_v\, p_F/\eta$ it is optimal to reduce electricity production to either zero or the production that connected with the heat production reflected in the c_m line in Figure 1. The choice for heat production depends on the relative shadow price.

For $p_e(t) < \frac{p_F}{\eta}$ *and* $p_h > c_v \frac{p_F}{\eta}$ production will be*:*

$$Q(t) = \begin{cases} 0 & for \ p_e(t) < MC_{um} \\ [0, Q_{\max}] & for \ p_e(t) = MC_{um} \\ Q_{\max} & for \ p_e(t) > MC_{um} \end{cases} \tag{15}$$

$$P(t) = c_m\, Q(t),$$

$$MC_{um} = -\frac{p_h}{c_m} + \frac{p_F}{\eta} \frac{c_m + c_v}{c_m}$$

Merit order electricity distribution for a given shadow price of heat.

With a given shadow price for heat the shadow price for electricity that satisfies electricity demand can be calculated by iteration. The use of a duration curve complicates this calculation and a simplification of this aspect is used in here. All plants are assumed to be available for production at any time and their heat production is assumed distributed evenly between winter and summer times. Plants are in reality not available for production at any time. There are provisional revisions and unanticipated breakdowns. To take account of this the capacity for all plants is characterised by a factor for availability. This can be individually specified but the default assumption is a factor of 0.8, which implies that the plant is available only 80% of the time. Availability is assumed evenly distributed over the 24 hours. The capacity of all plants will in the electricity calculations only be assigned 80% of the max capacity that are actually capacities.

For a given shadow price of heat marginal electricity production costs are calculated for each plant. These marginal costs are used to determine the level of production for each plant according to the demand profile captured in the duration curve.

The duration curve $P_D(t)$ captures the variability of demand during the 24-hour period. P_D is decreasing in time

$$\frac{d}{dt} P_D(t) \leq 0 . \tag{16}$$

$t = 0$ is peak demand and $t = \bar{t}$ is the minimum demand corresponding to the base load. The function:

$$\varphi(P) = P_D^{-1}(P)\, P + \int_{P_D^{-1}(P)}^{\bar{t}} P_D(t) dt \tag{17}$$

defines the duration curve as the time that demand is equal to P. The production of plant j' is defined by:

$$E_j = \varphi\Big(\sum_{i=1}^{j} \tilde{P}^i_{\max}\Big) - \varphi\Big(\sum_{i=1}^{j-1} \tilde{P}^i_{\max}\Big) . \tag{18}$$

Following the duration curve plants are assigned production in the base load segment[6] until this demand has been met. The production of the following plants of the cost ordered plants are restricted by the sloped part of the duration curve. Those plants are operating below max capacity.

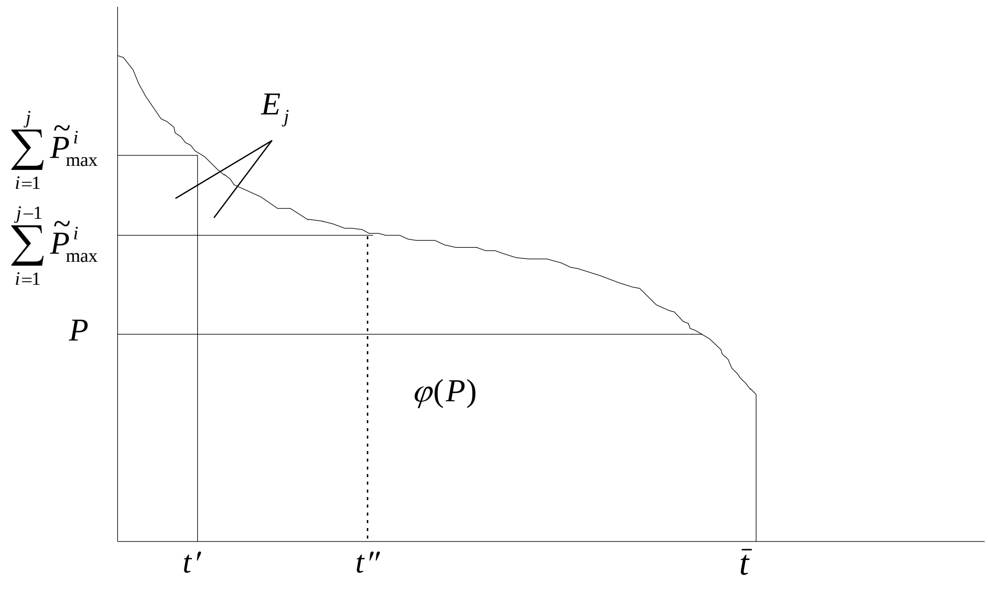

Figure 2 Duration curve for electricity demand

[6] Equivalent to producing all 24 hours or 8760 hours per year for the 80% of capacity. In the output calculation production time is measured in full load hours per year implying around 7000 hours for base load plants.

In Figure 2 the principle of (18) is illustrated. The electricity of plant *j′* is equal to the area E_j. This implies that plant *j′* produces electricity at max capacity in the in the interval 0 to t'. From t' to t'' the load is gradually reduced. At t'' the plant is not producing. Plant *j′* is characterised as a peak load supplier because of its relatively high marginal production cost. In the time interval t' to t'' this plant is the one adjusting to demand and thus serve as the marginal plant. This implies that $p_e(t) = MC_j$ in this time interval or:

$$p_e(t) = MC_j \quad for \;\; t \in \left[P_D^{-1}(\sum_{i=1}^{j} \tilde{P}_{\max}^{i}),\; P_D^{-1}(\sum_{i=1}^{j-1} \tilde{P}_{\max}^{i}) \right] \qquad (19)$$

The heat production of the plants H_j is calculated dependent on type. For condensing plants $H_j = 0$. For back-pressure plants heat production is:

$$H_j = c_m^j \, E_j \, . \qquad (20)$$

For the extraction condensing plant the heat production is determined depending on the regime of production along the Cm curve or the Cv curve. The calculation is carried out by dividing the extraction condensing plant in three parts of which one produces at the Cm line with positive heat and electricity output and another produces electricity with heat input along the Cv line. The heat output for the extraction condensing plant is found by adding the heat production and heat input in these two parts of the plant.

Determination of shadow price for heat.

The heat production for a given plant is depending on the shadow price for heat. The procedure of merit order described above has resulted in a total heat production:

$$H(p_h) = \sum_{j=1}^{n} H_j(p_h) \, . \qquad (21)$$

The final shadow price for heat is found from:

$$H(p_h) = \overline{H}, \qquad (22)$$

$\overline{H}$ is total heat demand.

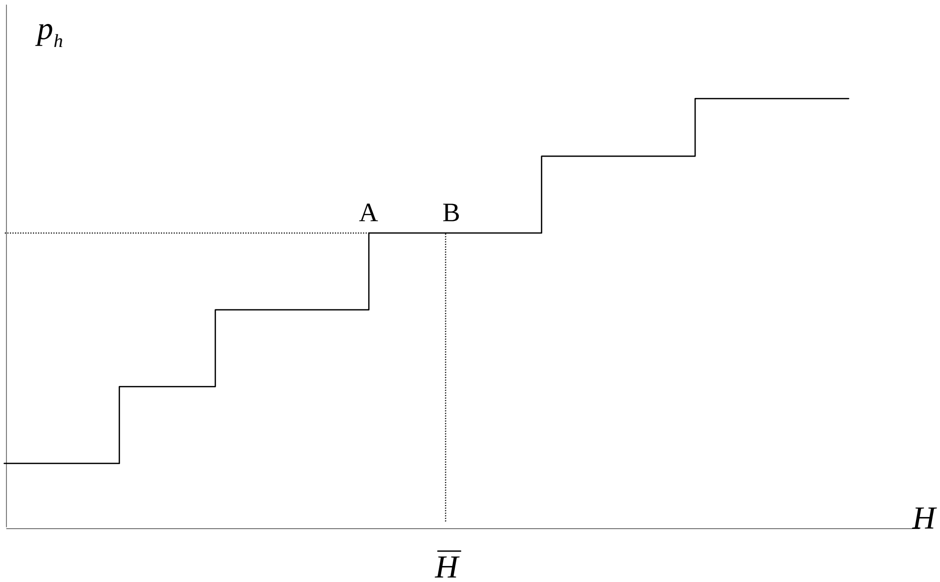

Figure 3 Supply curve for heat.

In Figure 3 the supply curve for heat illustrates the stepwise increase of supply for higher shadow price. The $\overline{H}$ vertical line shows how the shadow price is found as the marginal cost of the marginal plant (the horizontal dotted line). Production for the marginal plant is found as the distance A-B. An iterative procedure of changing the shadow price of heat secures that the demanded heat production is reached.

3.5 Total heat production

The final demand for heat is found in ADAM and transformed to energy terms demand. The share of CHP in heat production is projected as this is a major factor under public planning control. This share has increased considerably and continues to increase as district heating plants are converted to CHP and new district heating grids are established. The share and production for district heating plants are thus also given by projection. The fuel mix and efficiency of district heating plants are projected exogenously.

The heat production of decentral CHP is given by the operating time projection also used for electricity production calculations. Heat production in both utility and non-utility decentral CHP is in this way exogenous.

The residual heat demand is produced in central CHP plants and distributed on the individual plants by the optimisation procedure as described above.

3.6 Fuel consumption

Fuel consumption for electricity production is found from the consumption in the different categories. For some of the categories fuel consumption is directly given as they produce only electricity or use no fuel – but for the categories with joint production of electricity the total fuel used has to be divided on the two products electricity and heat. Another difference among categories is the fuel substitution possible in central plants compared to projected fuel mix in most categories.

The total fuel consumption for electricity and heat is distributed on fuels by the exogenous fuel shares for the secondary categories and district heating, whereas the central fuel consumption is found by adding over the individual plants. There are four different fuels coal, natural gas, fuel oil and biomass including waste.

Fuel consumption is found by converting electricity and heat production to fuel input by the electricity conversion efficiencies or total fuel efficiencies for CHP production. Fuel consumption is used for price determination (in value terms), in fixed price demands in ADAM (external balances etc.) and for emission calculations in energy terms.

The fuel consumption from different categories of electricity and heat production is schematically illustrated in the figure below.

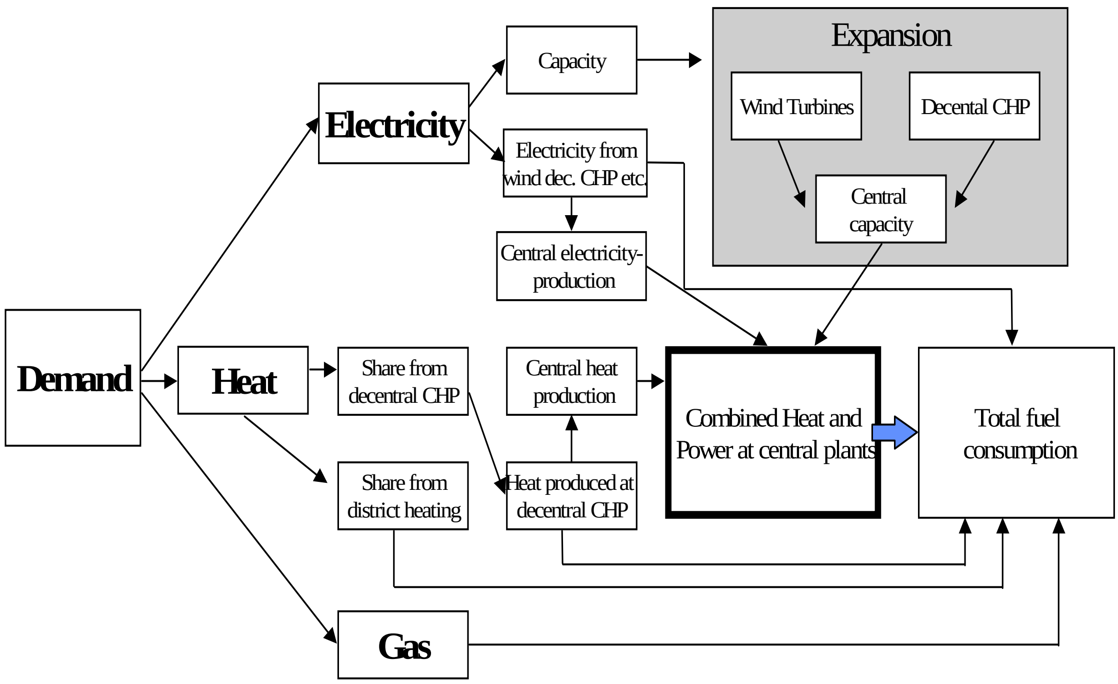

Figure 4 Fuel consumption in the model

Fuel consumption in central plants

Fuel consumption for the central plants is determined for each plant and for each fuel type by the total fuel efficiency or by electricity fuel efficiency for condensing plants. The fuel consumption is split between electricity and heat by Cv values and alternative fuel efficiency for electricity production.

The distribution of fuels on heat and electricity products can be done following a number of options.

a) Fuels can be split by assigning equal conversion efficiency for electricity and heat.

b) Heat can be considered the marginal product and the fuel consumption calculated as the reduced electricity production using the Cv value for extraction condensing and an alternative (electricity producing) condensing fuel efficiency for back-pressure plants.

c) Electricity production can be considered the marginal product and the fuel for heat calculated based on an alternative fuel efficiency, for example the one used for heat produced in district heating plants.

In Denmark there is some common practise and agreements regarding this distribution issue. For central production it is most often the option b) that is being used and this favours heat production based on large scale CHP (result in lowest cost). For decentral CHP the electricity production is most often considered marginal, which favours the electricity production from this category of plants.

In the model the option b) is used for central plants and the option a) is used for decentral plants. The efficiency advantage of CHP production on large plants is thus solely distributed in favour of heat production.

Fuel consumption for secondary categories

For the secondary categories only CHP and industrial cogeneration have fuel consumption. The principle for calculation of total fuel consumption and the distribution on products is the same for decentral CHP independent of owner ship. Decentral CHP is characterised by vintage specific fuel mix, efficiencies and Cm values as well as ownership differentiated number of producing hours. For each of the two ownership categories the different plants are assumed to have equal numbers of full load producing hours independent of vintage and cost characteristics. For industrial cogeneration it is only the electricity production that is assigned fuel consumption. No fuel consumption is assigned to wind and miscellaneous utility-owned.

For each category of decentral CHP (owner, fuel-type) electricity production is given from capacity and full load production hours. The heat production is given from electricity production and fuel specific average Cm value for all vintages. Fuel consumption for electricity production is calculated as

$$QE_t^j = \frac{E_t^j}{\eta_t^j} \tag{23}$$

η^j is the **total** fuel efficiency for each category and fuel specific group of plants and E^j is the electricity production from the owner category produced by fuel *j*. The corresponding fuel consumption for heat is calculated as

$$QH_t^j = \frac{\left(E_t^j \middle/ Cm_t^j \right)}{\eta_t^j} \tag{24}$$

where Cm^j is the fuel specific Cm-value (fixed electricity to heat ratio).

Cm and η values are for utility owned capacity calculated as an average for only CHP plants as neither wind nor miscellaneous are assumed to have fuel consumption.

For non-utility the average parameters for η are calculated from an aggregation of decentral non-utility CHP, industrial cogeneration and miscellaneous. Those three categories are assumed to have equal fuel mix and fuel efficiency for each vintage. Fuel consumption is calculated based on a total fuel efficiency as in (23). Industrial cogeneration and miscellaneous are assumed not to produce heat. To calculate fuel consumption for heat for the category non-utility CHP the average Cm value for this category is used to distribute the total fuel consumed in non-utility CHP as in (24) whereas the applied value of η is the average for the three non-utility categories.

When projecting fuel demand for secondary categories the most important influence comes from the improvement in total fuel efficiency and the expansion of each category. The composition of fuel in secondary categories is changed only with new vintages and no possibilities for substitution exist between fuel type groups. In projections the key political/planning parameters are expansion of categories and the fuel mix for these.

Fuel consumption on district heating plants

Fuel consumption is determined based on fuel efficiency, fuel shares and total district heating production. No capacity figures or production time is used here and no vintage characteristics either. Efficiency and fuel shares are projected for the total group of district heating plants.

Fuel costs for district heating is higher than for CHP heat production both because of higher fuel prices and because of lower efficiency. Fuel prices are higher for natural gas because the deliverance to district heating in Danish national accounts is assumed to come from the natural gas retail distribution sector and not directly from extraction as is the case for all input to the electricity producing sector (central CHP). This corresponds to the special price that utilities have been able to negotiate in recent years. Producing only heat is also less efficient than combined heat and power even in the case where the efficiency gain is evenly distributed on products as is the case for decentral CHP in this model.

The conversion of fuel from energy terms to fixed price demands

Fuel oil demand for electricity and heat production corresponds to two supplies in ADAM definition: Danish refineries and imports of refined products. The energy term fuel oil demand can be converted with the same factor (price per GJ in 1980) from the energy balance of Denmark.

The gas price for 1980 is not the gas price relevant for natural gas from the mid-eighties when the natural gas was first introduced for domestic use. Instead a 1980 price of 20 DKK per GJ is somewhat arbitrarily chosen. If the price from the energy balances were chosen the importance of natural gas fixed price demands would have been much higher. The input of natural gas can be defined as a deliverance from the sector of Danish extraction of oil and gas because gas imports have been very limited.

Biomass has no 1980 price as this fuel does not exist in the energy balances[7] and the fuel cannot be converted to fixed price with any reasonable price series from the national

[7] Biomass is included in the new energy balances but those were not available when the Hybris model was constructed.

accounts. The biomass is assumed to be supplied from Danish agriculture as straw and wood chips. Alternatively it could be distributed also on import of agricultural products, building material manufacturing etc.

3.7 Other inputs in electricity and heat production

The main input in electricity and heat production is fuel at least if the fluctuation of inputs is considered. Other inputs are described in less detail.

Employment in the sector is marginal for the total Danish economy and the labour costs are not of major importance for total costs. A change in fuel composition or change in technology does not give direct employment effects.

The only material input apart from fuel is supply from construction, but the model makes no attempt to relate this to capacity, grid size or age or investment activity.

Apart from fuel input all other material of labour input in electricity and heat is determined in the ADAM specifications that are depending on the level of output found in the iterative procedure with the bottom-up modules. Total factor income is only indirectly described by the price setting for electricity and to less extent price for heat and natural gas.

3.8 Price setting for electricity

Prices for output from the three energy sectors covered by this model are determined but the detail of the price setting varies a great deal. Electricity price determination via demand response creates the most important link between the energy models and ADAM. The ADAM price for electricity, heat and natural gas *pxne* is constructed in the energy model by an aggregation of the three prices for electricity, heat and natural gas. The demand response in ADAM at least for industry is thus to an aggregate price change, which reduces the demand reaction. Heat prices are determined based on fuel cost and exogenous investment cost. Fuel costs are less important for heat than for electricity. The price of natural gas is exogenous determined as the output price for the extraction sector *pxe* combined with a fixed cost related to grid. In the energy model prices are determined in DKK per. kWh or DKK per. GJ. When transferred to ADAM the aggregation includes a conversion to price indices.

First the most elaborated price setting mechanism for electricity is described. The description of electricity price setting is very detailed but still some issues of great importance cannot be adequately described. Electricity prices are depending very much on fluctuations in electricity exports and the price of this export. This element enters price setting in the way that according to legislation surplus from export activities have to be transferred to domestic consumers. This dependence on export activities can be exemplified by the average output price of electricity[8] that in 1990 was 45.97 DKK per. GJ. In 1991 the corresponding price was only 37.93 DKK per. GJ, which was caused by the large electricity export that year. Electricity exports are priced as a marginal product with much lower prices than domestic sales.

Danish legislation precludes the existence of profits in the power sector. This means that any profits of the total production and distribution system must be returned to consumers by adjusting the electricity prices the following year. This is included in the model as a no profit rule. Other features of Danish legislation are the very favourable

[8] Implicit prices from Danish national accounts.

conditions for appropriations connected to investments. In the five-year construction period of large power plants 75% of total construction cost can be appropriated and thereby included in electricity prices. Consumers hereby pay investments in the production and transmission capacity of the power sector in advance. The model takes account of this relation as well.

The energy model in Hybris only includes one electricity price. This price is calculated by following legislation and considering all cost elements to find an average production cost for electricity. In practise there are very different prices for different segments on the Danish market, but the prices all follow the average production costs very well[9]. Cost description has seven categories as included in Table 1. The negative number in surplus/deficit illustrates that an unanticipated surplus has to be returned to consumers the following year.

Table 1 Costs of electricity production and distribution 1993. Mill. DKK

Fuel	2506
Net import of electricity	98
Purchase from non-utility producers	473
Other variable costs	4370
Depreciation and appropriations	4640
Rents	137
Surplus/deficit	-37
Total costs (Mill. DKK)	12189
Total sales (GWh)	30625
Average cost per kWh (øre per. kWh)	39,8

Source: 10-year statistics. DEF 1994.

Electricity price formation is based on the seven cost categories, which are all projected by the model in a more or less endogenous way. The different cost elements that are the basis of price setting for electricity will be described starting with the two most endogenous elements investments and fuel consumption.

Fuel cost is found as described in section 3.6. The non-utility fuel cost is included in total fuel cost and therefore the purchase of electricity from non-utility producers is excluded. Imports/exports are treated separately[10] with a projected price for international trade. This price will fluctuate much depending on whether there is import or export a given year, but this interdependence has not been included in the model.

[9] Changes in spread between households and firms come gradually and have been very small.

[10] In the national accounts electricity is imported directly to consumers and this import reduces domestic deliverances. In the energy model imports are net imports defined as domestic demand from ADAM reduced for domestic production. Electricity import for each industry and private consumption are in the linked model projected in ADAM by constant coefficients so that the import share of final demand is constant. This projection is based on the average coefficient for the proceeding 10 year period. Contrary to this export is projected as constant level in GWh.

Depreciation and appropriation follow investments that are based on the modelling of capacity expansion. Hereby another endogenous element is added to the price determination. Investments in electricity production consist of a lot of categories of which a major part is exogenous. One group of investments is, however, endogenous directly based on expansion of capacity in the central production category. Investment in this category also constitutes a considerable share of investment for the electricity-producing sector.

For price setting only the total investments are relevant, but for the impact in ADAM investments have to be divided into machinery and buildings etc. In the energy sector *ne* covering electricity and heat production as well as natural gas retail distribution the investments in buildings etc. constitute the major share of investments which is in contrast to most other sectors in ADAM. Total investments in large plants for a given year are divided in machinery and buildings etc. by exogenously projected shares. For price setting the investments are used in current prices but for ADAM investments they are deflated by the investment price index *pi* from ADAM.

Central plant investments are determined by expansion directly. The investment for a given plant is distributed over the building period of five years. The expansion in MW is associated with an initial cost price per MW for each technology, which is then inflated by *pi.*

In a specific calculation the net present value of the five different central technologies is calculated from investment costs, fuel cost, and output. All other expenses are assumed equal for this calculation. The result is not an endogenous technology choice for large plants in this version of the model but the present exogenous technology choice can be changed to endogenous technology choice.

Investments associated with the building of a new large plant are distributed over a five-year building period. The distribution has been based on data for the building of large plants in Denmark during the years 1976-90.

$$I_t = 0.3 A_t + 0.34 A_{t+1} + 0.22 A_{t+2} + 0.09 A_{t+3} + 0.05 A_{t+4} \quad (25)$$

The investment I_t for a given year is determined based on the total investment for the plants completed that year, A_t, and the following four years.

Investments in secondary electricity producing facilities and other facilities.

The secondary electricity producing categories are treated based on the exogenous expansion projection. The building time for facilities of these categories is assumed to be on average one year. Investments are thus calculated based on expansion in MW and a per MW investment price. The investment cost per MW is assumed identical for windturbines with different ownership and also for decentral CHP. For decentral CHP it is possible to assign a share of investment cost to heat production. The default is set to refer all investment costs to electricity, but the exogenous cost has also been projected to reflect only the direct producing facility and not the district-heating grid. The category of cogeneration is included indirectly in prices through purchased electricity – the investments are not referred to electricity production.

Investments for three exogenous categories: electricity distribution facilities, environmental facilities and other investment incl. transport equipment are projected in current prices only.

Distribution facilities, grid, transformers etc. are depending both on the composition of the producing system, but also on the level of demand. The connections to abroad also count for this category of investments. It has been found very difficult to quantify these relations. As a consequence investments in the distribution system have also been projected exogenously.

Investments in environmental facilities have been of a considerable size but these investments have been initiated by direct regulation of emission quotas etc. Therefore this category will be independent of the level of demand and production. For new plants the investments are to a large extent included from the beginning.

As for central plant investments the individual projected investments are split on machinery and buildings etc.

Depreciation and appropriations

The investments determined in the model also serve as the foundation for cost element in the price setting. Depreciation and appropriations in the model follow legislation[11] in that depreciation can be included in price setting with the total construction costs for each facility deducted for appropriations. The depreciation has to be linear over 15 years starting with the first operational year of the facility. Appropriations can be made five years ahead of the first operational year and can cover up to 75% of the total construction costs. For each of the 5 years a maximum of 20% of the total construction budget can be appropriated.

Investments in large plants influence the price setting for at least 20 years. Five years ahead of operation there are appropriations, followed by 15 years of depreciation. This means that to project depreciation and appropriations information in the previous 15 years have to be taken into account.

Data for depreciation and appropriations in total exist for the period 1976-1993. These data are split by assuming that investments in the electricity sector can be split in investments in plants and other investments. These two categories of investments are characterised by a different time profile of investments. A plant is assumed to be built in a five-year period according to the profile shown in Table 2. The table shows the time profile that can be found[12] in data for ordinary utility-owned plant investments in the period 1976-1990.

Table 2 Investment profile for ordinary plant investments (% of total construction costs, fixed prices).

Year prior to operation start	1	2	3	4	5
Investment profile (%)	30	34	22	9	5

Source: ELSAM/ELTRA publications, Annual reports and DEF annual statistics.

[11] The Ministry of Trade 1977 departmental order No. 108.

[12] This profile is chosen so that for the period 1976-1993 the total square of deviation between actual and projected depreciation and appropriations is minimised.

Other variable costs

The fuel from non-utility plants was included in total fuel costs in the model. The rest of costs for non-utility plants are included in other variable costs for the sector as a whole as non-utility plants are assumed to have the same cost structure as utility-owned plants. The total costs for other material inputs are therefore projected based on the average cost (fixed price) per sold kWh in the period 1976-88. This average cost is calculated to 0.0424 DKK in 1980 prices per sold kWh, equivalent with 0.0737 DKK per sold kWh in 1990 prices. The projection inflates this cost element by the ADAM output price for the sector that produces building materials as 70% of materials input apart from fuels are supplied by this sector.

Labour costs are projected by using the ADAM determination of labour input and the 1990 labour cost per employee (196.279 DKK). This labour cost is projected by the wage index:

$$w_t = 0.4723\ lnahk_t + 0.5277\ lnfhk_t\ ,$$

lnahk and *lnfhk* are ADAM-variables for annual wages for workers and salary earners, respectively. Weights are the distribution of employment on workers and salary earners in 1990 for the electricity sector.

3.9 Price setting for heat and natural gas

Heat and natural gas price setting are described in much less detail than for electricity. The price of heat is found based on fuel costs as calculated for central CHP, decentral CHP and district heating plants using the cost splitting principles described in the section of fuel consumption. Apart from fuel cost only a fixed cost element covering capital cost of heating grids and capacity dependent operation costs enter the price calculation.

The fuel prices used are the same as for electricity fuel input except for natural gas inputs to district heating plants, which is priced as a retail deliverance from natural gas according to both energy balance data and tariffs from natural gas distributors. District heating production is not exempted from all fuel taxes as electricity production has been until recently.

Investments in heat production and natural gas distribution

Investment in heat production is exogenous. The major part of investments will be related to grids.

As central electricity investments in CHP are referred to electricity and decentral CHP by default has set the exogenous electricity share of investments to one, only district-heating plants involve investments. As the importance of this category is decreasing the investments in direct heat producing facilities will be very small. Investments in district heating grids have not been modelled and the assumption is that the grid is on large developed and less grid investments relative to the existing grid will be seen in the coming years. There is no time distribution of grid investments in the model and consequently these will have to be distributed exogenously if investments in grids are introduced in an exogenous projection. Prices are though to cover depreciation of the grid and this depreciation is projected by base year depreciation inflated by the investment price index from ADAM. Investments in this sector are split between machinery and buildings etc., which by default is set to referring all investments to the latter category.

Following this the price of heat is projected by total costs of heat production per unit produced.

The investments in natural gas retail distribution are fully exogenous, but the difference between the wholesale and the retail level can be difficult to identify when projecting grid investments.

The output price of natural gas distribution is nearly exogenous and treated by taking the international gas price (used as the fuel input price) and adding a constant mark-up[13] on this basic price including any possible taxes imposed on natural gas at this level. The assumptions regarding natural gas prices are very rough as actual prices among consumer groups vary a lot and also change in relative terms. This price constructed for natural gas distribution is used both in the aggregated electricity, heat and natural gas price (*pxne*) as well as for the fuel deliverance from natural gas distribution (*neg*) to district heating plants in the (*nev*) sector.

Aggregated output-price for the electricity, heat and natural gas sectors (ne).

The aggregated output price for the sector is constructed by calculating price indices for the three products with 1980=1 from the individual price series of price per kWh, GJ or M^3. The aggregated price index is constructed from adding production values in current prices based on the three individual indices and dividing by the fixed price production as determined by demand calculation in ADAM. This aggregate price index includes all taxes that are levied on the fuels used in the three energy sectors.

4. Residential electricity and heat modules

The description of the model for electricity, heat and natural gas in this paper focus on the supply of electricity and heat as well as the linking with ADAM. The bottom-up model for residential electricity demand is described only briefly corresponding to the description found in the other papers in the dissertation. A description of the heat model is excluded from this paper, mainly because of the very limited economic description in that model.

The model of residential demand for electricity is the one with most detail and most economic links. In the model energy demand for a given year is basically found by adding over the different appliances and the vintage characteristics

$$E = \sum_{s=1}^{n} \eta_S \sum_{i=t_0}^{t} B_{i,s} \ e_{i,s} \qquad (26)$$

$B_{i,s}$ Stock of appliance s, vintage i

$e_{i,s}$ Electricity consumption by each unit of appliance s, vintage in per unit of use

η_s Intensity of use for appliance s

[13] Actually the 1991 price on the deliverance from extraction *e*-sector to energy converting sector *ne* relative to the output price of *neg (natural gas distribution)* sector is used to give the mark-up for natural gas distribution output price.

The stock of appliance s of vintage i at time t is given by

$$B_{i,s} = S_{i,s}(1-a_{i,s})^{(t-i)} \qquad (27)$$

where $1/a_{i,s}$ is average lifetime for the vintage of appliance s; and $S_{i,s}$ is the size (sales) of vintage i of appliance s.

The vintage model is combined with an epidemic model of technology diffusion. The development in the stock of appliances is assumed to be determined by penetration ratios for households (share of households, which have a specific appliance). Penetration ratios are specified as following logistic functions, and for some of the most important appliances parameters of these functions are estimated. The logistic function implies that saturation levels exist. For example, it is natural to assume that a household would never have more than one washing machine. In epidemic models the usual assumptions about the development of penetration ratios exclude income and price effects on the stock of appliances. In the model applied here this is modified by letting annual sales for a number of the most electricity intensive appliances depend on the development in consumption of durable consumer goods as determined in the macroeconomic part of the Hybris model. If the resulting annual sales increase the penetration ratios too fast the economically linked sales figures are adjusted downwards to avoid exceeding the saturation levels. This effect will in the longer run tend to decrease the sales figures and hereby electricity demand as penetration ratios are approaching the exogenously given saturation levels.

5. Linking the energy models and ADAM

In this section the principles possible and the problems arising when linking models of very different kinds are described. Also linking procedures and relations linking variables of different kinds and definitions in the two models are described.

The methodological problems regarding different principles for linking the two models are also covered by the paper: "Integrating the bottom-up and top-down approach to energy-economy modelling. The case of Denmark". Therefore this section mainly deals with the practical implementation of the mixed linking principle – the hybrid approach.

5.1 Exogenising top-down energy variables in ADAM and adjusting input-output coefficients

As ADAM is a macroeconometric model applied in many different kinds of analyses and used by a lot of different institutions during the last 25 years the model includes all possible handles and variables to exogenise or adjust endogenous parameters of the model. This is also the case for energy where demand for energy input in all sectors can be adjusted, as well as the deliverances to energy input. This flexibility for energy relations is not necessarily the case for other top-down models. Energy input is in many other models determined in factor demand relations with, for example, energy in an aggregate of energy and capital.

ADAM includes an input-output system that also covers energy goods and goods that are more or less equivalent with fuels. To link fuel demand in electricity and heat production to ADAM many input-output coefficients have to be adjusted.

To create submodels that generate or split demand components from ADAM it is also convenient that ADAM basically is using fixed input coefficients for energy inputs. A module that generates specific demands for electricity, heat and natural gas can be constructed from national accounts and the aggregate input coefficient in ADAM of the *ne* sector product.

For private consumption of electricity and heating there is no aggregate coefficient adjustment. For imports of refined products to private heating consumption there is especially the option of introducing a trend for increased imports relative to deliverance from Danish refineries. The adjustment of energy coefficients in most cases needs to take into account also the possible adjustment of refined product imports. This implies that linking with ADAM in many cases creates the need to calculate adjustment parameters for ADAM based on a long range of ADAM variables.

Linking the models includes exchanging a lot of variables of which some are basic inputs to the other models and some are only variables needed to calculate adjustment variables correctly. This is caused by the simultaneous characteristics of ADAM. The exchange of variables in the iterative procedure between ADAM and the energy models requires that procedures for updating and extracting information in two different software packages are constructed.

5.2 Definitions of energy goods with inconsistencies between domestic produced energy and imported energy

There are big differences between ADAM and the energy models regarding the classification of energy goods. Energy models are constructed to handle energy as a fuel and especially with the purpose of examining the emission property of different fuels. ADAM is on the other hand focusing on SITC import classification and domestic production sectors. Therefore some definitional problems exist:

- Energy goods are defined differently or are totally absent in the ADAM model
- The units used for energy are different - fixed prices versus energy units
- The division of fuel input on delivering sector whether import or domestic is not conducted in the energy models
- ADAM does not treat energy as separate fuels but are focusing on the production created in the domestic sectors and the import categories

The energy models have a detailed fuel calculation with four fuels that are not directly corresponding to the classification used in ADAM. Therefore the linking requires that a set of assumptions regarding the delivering sector or import component are made.

5.3 The need for iterative procedures

The solution to the linking chosen for the Hybris model implies that an iterative procedure of exchanging price and demand variables between ADAM and energy models must result in demand responses levelling out. The alternative would be models that determined fuel demand in energy models based on economic developments in ADAM and probably an input to ADAM determining price for electricity and heat. The iterative procedure has advantages in the important link between fuel prices including taxes, the expansion of capacity and the demand response to price developments. For most other transferred variables the iterative procedure only changes variables marginally compared to just transferring once. The linking compared to integration of the energy models in ADAM also simplifies possible changes in energy models that would have been more difficult to directly implement in ADAM.

5.4 Arguments for choosing to link the specific energy elements as opposed to other parts of energy demand and supply

In Hybris it is chosen to link especially the electricity and heat supply to ADAM as this is seen as the most important single sector for the description of fuel use and emissions. Also residential demands for electricity and heat are seen as important areas for bottom-up description as the demands here are depending on stock characteristics and technical composition of a large number of devices etc.

The linking has been established so that it is possible to analyse the interaction between attaching or detaching the three energy models. For example, the models of residential electricity and heat demand can be detached and this will increase demand response to price increases as price elasticities are much higher in the ADAM description than in the two bottom-up energy models that describe the same area of demand.

The model of electricity, heat and natural gas

ADAM includes only little detail for the sector supplying electricity, heat and natural gas compared to the energy importance of this sector. This sector is important for all analysis of emission reduction, as it is a sector where fuel substitution options are very pronounced but not measurable in the ADAM context of elasticities. The sector is also very suited to describe by bottom-up modelling approaches as the investment decisions are very long-term and there is a limited number of producing units that can be characterised by technical parameters associated with each unit. Therefore this sector was chosen to be described by a separate energy model and linked to ADAM so that demand responses to the price-setting taking place in the energy model were included. The link between this model and ADAM does only increase the analysing capability of ADAM and make the description of the sector more realistic. Linking these elements does not imply changing any economic characteristics of ADAM or decreasing the dependence of energy demand on economic factors.

The linking of ADAM and the energy model for electricity, heat and natural gas has implications on ADAM energy demand, producer costs, wage setting, international competitiveness and the trade balance. But the effect on the economy of changes in the energy sector in general has only limited effect on the main economic variables in ADAM.

Apart from prices also fuel consumption and investments in the energy sector are transferred to ADAM, but the effects of these links are in general less than the effect of price setting.

Residential demand for electricity and heat

Residential energy demand has been modelled in many bottom-up models. Therefore it was chosen as an interesting area for linking as the consequence of using (attaching/detaching) the bottom-up description as opposed to the top-down description in ADAM could be studied. The energy consumption in this element of energy demand is also considerable and has been (is) a main target for regulating both technical and planning aspects. Also the energy consuming equipment can be grouped in some relatively homogeneous categories that can be described with technical parameters.

As opposed to the model of electricity, heat and natural gas the model for this final demand component has reduced the importance of economic characteristics relative to the description in ADAM. The impact on ADAM variables apart from energy demand itself is of limited importance.

The ADAM demand component for residential electricity and heating demand is replaced by two independent bottom-up energy models. These two models are very similar in approach although the residential electricity demand module includes much more detail and technical options. The heat demand is driven by investments in new dwellings in ADAM, whereas the electricity demand to less extent is driven by economic factors as the price of electricity and the consumer purchase of durable goods.

Energy demands in the two residential models are aggregated converted to fixed price figures and replace the demand component in ADAM (*fCe)*. The input coefficients in ADAM *fCe* are adjusted so that the fuel input found in the residential energy models corresponds to delivering sectors to *fCe*. Some of these ADAM coefficients are exogenous and some can be adjusted by adjustment parameters that by the iteration procedure between energy models and ADAM secure that the bottom-up determined coefficient value can be transferred to ADAM. As also total residential energy demand in ADAM is changed and this demand component is part of the consumption system of ADAM the total private consumption restriction has to be kept by adjusting the other consumption components of ADAM. This is one of situations in which the iterative linking procedure establishes that the sum of consumption components matches the aggregated private consumption in ADAM.

Why not bottom-up models for other parts of energy demand?

There are several reasons that other parts of energy demand have not been modelled by bottom-up models. Industry energy demand is of limited importance in most industries in ADAM. The energy is consumed in production processes and in devices that vary much and it is therefore difficult to identify technical parameters that can be described or projected as anything else than just averages. The top-down description of energy demand in ADAM is seen as having many advantages compared to a bottom-up description for which the data collection and construction work would have been comprehensive compared to the relatively small share of total energy demand than can be referred to an individual production sector in ADAM.

Transport energy demand is an area that is interesting for a description by bottom-up models. The technologies for transport can be grouped in some relatively homogenous categories and the fuel input is the main input apart from capital in the production of transport services. No bottom-up models for this area of demand have been linked to ADAM, mainly because the other areas of demand were preferred due to availability of data.

Main channels for impact from energy system to the economy

The relation between changes and developments in the energy system and the economy is much better described in the linked model of Hybris than by ad hoc adjustments in ADAM. The three main channels for the impact on the economy are:

- Price on electricity and heat and the demand response
- Changed fuel consumption and fuel mix influence trade balances and agricultural production
- Investments

The dominating channel is the first price setting property (*pxne)* of the energy models.

The impact of linking on the property and analytical capabilities of the energy model

The linking implies that two major questions can be addressed by the model.

- How is energy demand and hereby the electricity and heat production influenced by changing macroeconomic conditions?
- To what extent are electricity and heat production influenced by demand feed-backs induced by prices following changes in the electricity and heat production system as, for example, the introduction of taxes on fuel or rapid expansion of renewable energy technologies?

Consistent analyses of CO_2 taxes and other emission reducing initiatives

For analyses of energy policy and emission reducing targets there is a fundamental difference on the initiatives that would have been conducted in ADAM and in the bottom-up energy models. ADAM would mainly have been used for analysis of taxes or emission quotas whereas the planning and technological options would have been explored in the energy models. But there are important interdependencies, which have to be taken into consideration for a more complete analysis. In Hybris it is possible at the same time and in a consistent way to analyse initiatives of these two different kinds.

Fuel taxes influence demand developments which again have implications for the capacity and expansion of the electricity and heat supply system. Taxes can in some cases result in reduced demand that postpone or reduce the expansion of capacity. Hereby the new and efficient technologies will be postponed and the average fuel efficiency be lower which tend to increase prices reducing demand even more than anticipated but maybe not reducing fuel consumption proportional to the reduction in final demand. The flexibility of the fuel choice and hereby the effect of a CO_2 tax will also be reduced if new multi-fuel technologies are postponed.

Initiatives that are changing the composition of electricity or heat producing capacity can have larger effects on emissions than anticipated if this restructuring is associated with higher costs that result in a reduced final demand in ADAM.

5.5 Calculating electricity, heat and natural gas demand in ADAM

ADAM only describes demand for the aggregate *ne* sector production consisting of electricity, district heating and natural gas distribution. Based on national account statistics this demand is split on the three components by splitting the ne input in all uses in ADAM in three by io-coefficients. The final demands *fxnel, fxnev* og *fxneg* are calculated in a PCIM module so that the sum of the three demand components always matches the total *fxne* that continues to be determined by the ADAM relation. This is only modified for the deliverance from neg sector to *nev* and *nel* to *nev*, which are coefficients that influence the total *anene* coefficient. The calculation of these coefficients is further described below in the section dealing with output variables transferred to ADAM. A PCIM module "**LINKEFTM"** calculates the demand for the three types of energy and project a lot of split input-output variables. Finally, these variables are extracted and transferred to the input file to the visual basic modules handling input to the energy models.

The **LINKEFTM** also construct io-coefficients for the three energy goods so that the sum of these corresponds to the aggregated coefficients for *ne* sector input in other sectors. All energy inputs for a given sector are proportionally reduced when efficiency is improved. This is needed if an exogenous energy efficiency trend (*dtfve*-variables) for total energy input in each sector is included in energy relations. This efficiency improvement must not only reduce total energy demand but also the demand for electricity heat and natural gas.

Other variables transferred to the energy models from ADAM

Other variables are transferred to the energy model of which some are price variables on imported fuels *pm3r, pm3k og pm3q*, consumer prices in total *pcp* and for the residential electricity and heat demand *pce*, net consumer prices for the same component *pnce* and the price on investment goods *pi*. These are used for inflating in the energy models and for calculating adjustment variables that are returned to ADAM.

Production variables are also used for calculating correction factors and adjustment parameters to ADAM and include electricity, heat and natural gas *fxne*, refining *fxng* and extraction activities *fxe*.

Tax rates *tsds* and *sds* are transferred to calculate revenue recycling etc. CO_2 emissions are calculated from ADAM based on *fm3k, fm3q, fe3* and *ange3*.

Another demand variable is constructed in LINKEFTM as a variable for domestic demand for electricity is needed to calculate expansion in the electricity sector. This variable *bjeldk* is calculated based on the same io coefficients that were used for production *fxnel* but reduced for electricity export *anele3* and with imported electricity to each final use added with the coefficient of 1990.

Finally, a range of informative variables is transferred to the energy models for calculations of quotas etc. A total of around 40 variables is transferred to the energy models.

5.6 Linking fuel demand in energy models and ADAM

First the level of total fuel demand found for electricity heat and natural gas distribution has to be adjusted in ADAM. In ADAM there are relations for each of the fuel input coefficients in the *ne* sector an adjustment parameter that scales the coefficient so that the sum of coefficients corresponds to the fuel demand found in the energy model. Thus, adjusting total fuel input in ADAM also establishes that the fuel coefficients are adjusted not necessarily to the correct level but from that state the further adjustment parameter can be calculated afterwards.

In ADAM fuel input in the *ne* sector is given as

$$fvene_t = ((e^{(\log(fvene_{t-1})+1.3833\,(\log(fxne_t)-\log(fxne_{t-1}))-0.1917\,(\log(fxne_{t-1})-\log(fxne_{t-2})) -0.1917\,(\log(fxne_{t-2})-\log(fxne_{t-3}))-(\log(dtfvene_t)-\log(dtfvene_{t-1})))}) (1+jrfvene_t))(1-dfvene_t) \quad + dfvene_t\, zfvene_t \tag{28}$$

The exogenising dummy *dfvene* is used to exogenise the relation so that total fuel input is found as the exogenous *zfvene*.

$$zfvene = fxne(am3kne + am3qne + angne + aene + anene) \tag{29}$$

Input coefficients are those determined in the energy model. In ADAM the correction factor *kvene* is used to secure that total energy input *fvene* always corresponds to the specific fuel inputs calculated by input coefficients *am3kne, am3qne, angne, aane* etc. When the correspondence is secured in the energy models by calculating input-coefficients based on fuel input and production value *fxne* the *kvene* factor will equal to one once all the variables in ADAM that determine *kvene* in (31) have been adjusted. This fact makes the adjustment of individual input coefficients simpler.

$$kvene_t = \frac{\frac{fvene_t}{fxne_t} - dxm3k_t\, am3kne_t - aane_t - aene_t}{angne_{t-1} + jdangne_t + anene_{t-1} + jdanene_t + (am3kne_{t-1} + jdam3kne_t)(1 - dxm3k_t) + am3qne_{t-1} + jdam3qne} \qquad (30)$$

Input of imported coal can be calculated directly from fuel demand (TJ) in the energy model. This fuel demand can be found by adding fixed price demands for electricity and heating.

$$fm3knel = F_{kul}^{el}\ k_{kul}^{el} \qquad ; k_{kul}^{el} = 10.092 \quad (31)$$

$$fm3knev = F_{kul}^{varme}\ k_{kul}^{varme} \qquad ; k_{kul}^{varme} = 11.08 \quad (32)$$

Then demand is converted to the io-coefficient and the necessary adjustment parameter in ADAM.

$$am3kne = \frac{fm3knel + fm3knev}{fxne} \qquad (33)$$

$$jdam3kne_t = am3kne_t - am3kne_{t-1} \qquad ; t = 1995, \ldots, 2022 \quad (34)$$

The ADAM relation for the coal import coefficient is included below.

$$\begin{aligned} am3kne_t = {} & dxm3k_t \frac{(am3kne_{t-1}\ fxne_{t-1} + jdfm3kne_t)}{fxne_t} \\ & + (1 - dxm3k_t)(am3kne_{t-1} + jdam3kne_t)\, kvene_t \end{aligned} \qquad (35)$$

Adjustment of the coal import coefficient for electricity and heat production can be done by using the *jdam3kne* as determined in (34), when *kvene* is 1 and *dxm3k* is 0. The import level of coal *fm3k* includes the component used in electricity and heat through *am3kne* (36).

$$fm3k = am3kne\ fxne + am3knb\ fxnb + am3kce\ fce + am3kov\ fxov + film3k + am3ke3\ fe3 \qquad (36)$$

The ADAM relation for the input coefficient of imported refined oil is.

$$am3qne_t = (am3qne_{t-1} + jdam3qne_t)\, kvene_t \qquad (37)$$

This import component includes both refined oil products as well as imported electricity. The imported electricity for use in electricity, heat and natural gas is very limited, corresponding to the small electricity input (own use) in the sector. Therefore the assumption will be that there is no electricity in this imported input and it only covers refined oil products (fuel oil). The energy model first determines aggregate fuel oil input, which then has to be split into a deliverance from import *fm3q* and a deliverance from domestic refining *ng*. The total input coefficient for fuel oil is found as,

$$afuelne = \frac{F_{fuel}^{el}\, k_{fuel}^{el} + F_{fuel}^{varme}\, k_{fuel}^{varme}}{fxne} \tag{38}$$

The split is carried out based on the composition of the deliverance in the base year 1990 and assumes unchanged composition. Import deliverance coefficient is found as,

$$am3qne_t = \frac{am3qne_{90}}{am3qne_{90} + angne_{90}}\, afuelne_t \tag{39}$$

The implementation in ADAM *am3qne* is carried out by using the adjustment parameter *jdam3qne*. The adjustment *jdam3qne* is calculated by assuming *kvene* = 1 and as,

$$jdam3qne_t = am3qne_t - am3qne_{t-1} \tag{40}$$

The input of domestically refined products *angne* is calculated in the energy model in line with imports of refined products *am3qne* in (39):

$$angne_t = \frac{angne_{90}}{am3qne_{90} + angne_{90}}\, afuelne_t \tag{41}$$

The ADAM relation (42) is used to adjust *angne* by assuming *kvene* = 1 and using the adjustment parameter *jdangne* in (43) that is calculated based on the coefficients found in the energy model.

$$angne_t = kvene_t\,(angne_{t-1} + jdangne_t) \tag{42}$$

$$jdangne_t = angne_t - angne_{t-1} \tag{43}$$

An increased use of for example natural gas in electricity and heat production will decrease both refined product import and the supply from domestic refineries. In the ADAM March 1995 version the coal import can either be chosen to be decreased in the same proportion as refined imports, domestic refined products and the deliverance from the *ne* sector itself or to be kept constant. It is reasonable in ADAM to have fuel oil as marginal fuel and therefore adjust the two corresponding coefficients when total fuel input has changed for example due to large production changes, but not if the issue is improved fuel efficiency on average. Following the first option an improved fuel efficiency adjusted in ADAM by *dtfvene* will reduce import of coal, import of refined products, domestic refined products and own sector input, but not natural gas from the extraction sector *e* (that is exogenous) and the deliverance from agriculture (biomass).

In (44) the ADAM deliverance coefficient from the extraction sector, that includes wholesale natural gas, for input to electricity and heat is given,

$$aene = \frac{bene\ fxe}{fxne} \tag{44}$$

Extraction of crude oil and natural gas sector *e* is exogenous in ADAM, whereby the supply coefficient *aene* from *e* sector has to be defined as above. The share of extraction production *bene* that is supplied to electricity and heat production is exogenous. The coefficient *aene* in ADAM has to be determined by *bene*, which is done by calculating *bene* in the energy model.

$$bene = \frac{aene\ fxne}{fxe} \tag{45}$$

where *aene* in the energy model is determined as,

$$aene = \frac{(F_{gas}^{el}\ k_{gas}^{el} + F_{gas}^{varme}\ k_{gas}^{varme} + bjgas\, k_{gas}^{el})}{1000\ fxne} - anegne \tag{46}$$

The variable *bjgas* is the final (retail) demand for natural gas determined in ADAM in energy units. This demand includes the *ne* sectors own deliverance that is also included in (46), as the second element in the numerator includes both the natural gas deliverance from the *ne* sector to district heating and the deliverance from extraction (*e* sector) directly to CHP production. Therefore, to avoid double counting the *anegne* (natural gas distribution sector *neg* deliverance to the *ne* sector in total) is subtracted in (46).

$$anene \equiv anegne + anelne + anevne \tag{47}$$

The total deliverance from electricity heat and natural gas distribution to the sector itself is defined as the sum in (47). As the heat inputs *anevne* are zero and *anegne* is only used for input in the heat sector the calculation is simplified.

$$anegne_t = \frac{F_{gas\ \ t}^{fjernvarme}\ k_{gas}^{varmr}}{fxne_t} \tag{48}$$

The deliverance from natural gas distribution *anegne* is only for use in district heat production. CHP natural gas input is contrary to this delivered only from extraction sector *e*, which can be observed in the missing deliverance from natural gas distribution to electricity production in the national account statistics.

For electricity input in the *ne* sector it is assumed that the coefficient *anelne* is constant at 0.0031. By this the *anene* coefficient is given from (47) and this coefficient can be transferred to ADAM by using the adjustment parameter *jdanene* in the ADAM relation (49).

Both the *anegne* and the *anelne* coefficient are transferred to ADAM for use in the LINKEFTM ADAM sub-model that calculates demands for electricity, heating and natural gas separately. A consistent calculation of the total demand for *ne* sector production (*fxne*) and the demand for the production-subsectors electricity, heat and natural gas can thereby be secured.

$$anene_t = kvene_t\,(anene_{t-1} + jdanene_t) \qquad (49)$$

All five fuel coefficients determined in the energy model for input in ADAM, are included in some of the ADAM relations for the *ne* sector. Therefore, it is necessary to assure consistency between the aggregated calculations for the *ne* sector and individual fuel inputs.

Apart from the fuels described above the use of biomass found in the energy model must be transferred to ADAM. With the March 1995 version of ADAM the coefficient *aane* for deliverance from agriculture to the *ne* sector is now included. In the energy model it is assumed that biomass is an agricultural product, which can be either straw, biogas or energy crops.

$$aane_t = \frac{fane_t}{fxne_t} \qquad (50)$$

The fixed price input of agricultural products *fane* is determined in the energy model and being an exogenous ADAM variable it can be directly transferred to ADAM.

$$fane = F_{bio}^{el} k_{bio}^{el} + F_{bio}^{varme} k_{bio}^{varme} \qquad k_{bio}^{varme}; k_{bio}^{el} = 20 kr.\,pr.\,GJ\,i\,1980 \quad (51)$$

5.7 Linking prices and securing consistent price projections

In ADAM the output for the *ne* sector (electricity, heat and natural gas) has one uniform price (*pxne*). In the energy model there are three output prices *pxnel*, *pxnev* og *pxneg*. The aggregated price *pxne* is constructed from the three sub-sector prices. This aggregated price index is the main channel for linking effects.

The effect of changes in underlying prices thus have an identical effect in ADAM regardless of the composition of input (electricity, heat or natural gas) in a given sector. The only difference is created by the response to electricity price for residential electricity demand. The demand response to a given change in *pxne* will be identical for all three inputs in a given sector, but the aggregate effect on electricity, heat and natural gas demands can differ as the input shares of the three energy types can be different for sectors with different price elasticity. An improvement for this price response can be achieved by using the results of the SMP project that split energy demand in ADAM manufacturing sectors in three types, with electricity as a separate energy input.

The change from the ADAM 1991 to the 1995 version has accomplished an approximate doubling of energy price elasticities, which have increased the importance and effect from price changes on electricity, heat and natural gas. The importance of the price determination in the *ne* sector has hereby increased considerably, which adds to the arguments for linking ADAM to the energy model for electricity, heat and natural gas.

The price index *pxnex* is constructed in the energy model as,

$$pxnex = \frac{pxnel\ fxnel + pxnev\ fxnev + pxneg\ fxneg}{fxne} \tag{52}$$

In ADAM *pxne* is exogenised by using the dummy *dpxne* equal to 1. In ADAM *pxne* is determined as,

$$pxne = dpxne\ pxnex \tag{53}$$

The price of fuels and final energy must be consistent between ADAM and the energy models. Prices can be projected in either ADAM or in the energy models and then linked to ADAM. It was chosen to project energy prices in the energy models and then transfer all relevant price variables to ADAM as some of the fuel prices in the energy models are not used in ADAM directly. Fuel prices have been taken from input-output- and energy matrices for historical years and projected following the projections from the Danish Energy Agency, that to a large extent are based on IEA projections.

The price of crude oil *pm3r* is exogenous and the dominating energy price in ADAM. Most other fuel prices are by default projected with the same growth rate as crude oil. It is possible to make adjustment and corrections to this crude oil dependency, which is especially used for projecting the prices following Danish Energy Agency and energy models output.

The energy model converts fuel prices in DKK per. GJ to price indices according to the indices that ADAM uses. Consistency is secured by constructing energy prices as below by using the exogenous *pm3r*,

$$pm3r_t = pm3r_{t-1} \frac{råoliepris_t}{råoliepris_{t-1}} \tag{54}$$

In ADAM the price for imports of refined products *pm3q* follow crude oil prices.

$$pm3q_t = \left(pm3q_{t-1}\ kpm3q_t\ \frac{pm3r_t}{pm3r_{t-1}} \right) (1 + jrpm3q_t) \tag{55}$$

The growth rate can be adjusted relative to *pm3r* by using *kpm3q.* This variable is used to generate the same price development for *pm3q* as for fuel oil in the energy model if a difference in growth rates between crude oil and fuel oil is projected.

$$kpm3q_t = \frac{fuelpris_t}{fuelpris_{t-1}} \frac{pm3r_{t-1}}{pm3r_t} \tag{56}$$

For the price of coal imports a similar adjustment in ADAM of growth rates is possible.

$$pm3k_t = \left(pm3k_{t-1}\ kpm3k_t\ \frac{pm3r_t}{pm3r_{t-1}} \right) (1 + jrpm3k_t) \tag{57}$$

The energy model generate another coefficient for growth in coal prices as,

$$kpm3k_t = \frac{kulpris_t}{kulpris_{t-1}} \frac{pm3r_{t-1}}{pm3r_t} \tag{58}$$

Price on output in extraction of crude oil and natural gas in ADAM follow crude oil prices including import tariffs as given in (59).

$$pxe_t = \left(pxe_{t-1} \frac{pm3r_t + tm3r_t}{pm3r_{t-1} + tm3r_{t-1}} \right) (1 + jrpxe_t) \tag{59}$$

The adjustment of this price in ADAM involves two different prices used in the energy model as both crude oil and natural gas are included in the *pxe* price. If price developments are identical for these two series and there are no changes in the share of natural gas (*bene*) and the fuel oil share then there is no need for adjustments in ADAM. But price developments can be diverging as well as share changes are probably occurring. Another tricky fact is that natural gas input in *ne* has the same price as crude oil delivered to refineries. In the energy model two prices for natural gas are used as the deliverance from natural gas distribution sector *neg* to heat production use the price *pxneg*, whereas extraction sector natural gas has it own price (internationally given). The following calculation adjusts for these facts.

$$jrpxe_t = \frac{\left(\frac{råoliepris_t (1 - bene_t) + gaspris_t \, bene_t}{råoliepris_{t-1} (1 - bene_{t-1}) + gaspris_{t-1} \, bene_{t-1}} \right)}{\frac{pm3r_t + tm3r_t}{pm3r_{t-1} + tm3r_{t-1}}} - 1 \tag{60}$$

The change in the weighted price of crude oil and natural gas is compared to the change in the ADAM crude oil price including tariffs. It is assumed that all the deliverance from extraction sector *e* to sector *ne* is only natural gas, whereas the remaining extraction is crude oil and delivered to other users than the *ne* sector.

For the price of domestic refineries output *pxng* it is assumed that the price corresponds to fuel oil prices. This price is determined in ADAM following the price of imported refined products *pm3q* with import tariffs added and with pm3q adjusted as described above. Fuel prices in the energy model do not include tariffs as they are missing real importance at present levels.

5.8 Investments in the energy sector linked to ADAM

Investments in electricity, heat and natural gas are described in the energy model based on expansion of capacity, investment prices and investment profiles in time.

The direct linking to ADAM is complicated for investments in buildings etc. because investments in this category are determined as part of the aggregate determination of building investments in ADAM. Machine investments are determined separately for each sector in the 1995 ADAM version, which makes adjustment much easier. Machine capital in the *ne* sector can be exogenised and hereby also investments. Machine investments are transferred to ADAM by exogenising capital using *zfkmne* in the ADAM relation as below.

$$fkmne_t = \left(e^{\substack{(\log(fkmne_{t-1})+0.2(\log(fkmnew)-\log(fkmnew_{t-1}))+0.2(\log(fkmnew_{t-1})-\log(fkmnew_{t-2}))+0.2(\log(fkmnew_{t-2})-\log(fkmnew_{t-3})) \\ +0.2(\log(fkmnew_{t-3})-\log(fkmnew_{t-4}))+0.2(\log(fkmnew_{t-4})-\log(fkmnew_{t-5})))}} \right. \\ \left. (1+jrfkmne_t)\ \ (1-dfkmne_t)+dfkmne_t\ \ zfkmne_t \right) \quad (61)$$

Machine capital is calculated from the aggregated investments *fimne* in the energy model for electricity, heat and natural gas distribution.

$$zfkmne_t = 0.85\, zfkmne_{t-1} + fimne_t \quad (62)$$

For investments in buildings etc. it is possible to use the difference between building investments in ADAM and the same investments determined in the energy model to update adjustment parameters in ADAM until the warranted level of investment in ADAM is reached. Parameters *jdfipb* or *jvipb1* in the total building investments or the exogenous component in the ADAM relation for extraction sector building investment *fieb* can be used. Total exogenous building investments in ADAM seem to be an unattractive solution as this exclude effects on other sectors building investments. A somewhat arbitrary adjustment using *jvipb1* is shown below could give the warranted level of building investments in the *ne* sector of ADAM.

$$jvipb1_t = 7(fibne_t^{Forsyn} - fibne_t^{ADAM}) + 0.075 \sum_{t=-14}^{-1} jvipb1_t \quad (63)$$

For this adjustment parameter too it is assumed that it is not already being used. However, there are problems with the simultaneous effects of this adjustment, so the investments in buildings etc. for the sector are following the normal ADAM determination instead.

Building investments are affected by the aggregate production measure *fxvb* in ADAM that includes building investment weights (building investment quotas) for each sector. The weight for the *ne* sector is very high 3.5, which is about the highest weight. Total building investments will therefore be relatively strongly affected by changes in production in the *ne* sector.

In the 1995 ADAM version the building investments in the *ne* sector are determined by the change in gross domestic product at factor costs for the *ne* sector *fyfne*, but only for the part of investment that is not included in the exogenous building investment component *fieb*. The ADAM relation has the following form.

$$fibne_t = fieb_t - fibe_t + (fibne_{t-1} - (fieb_{t-1} - fibe_{t-1}))\left(\frac{fyfne_t}{fyfne_{t-3}}\right)^{\frac{1}{3}} \frac{1}{kfibp_t} \quad (64)$$

5.9 CO_2 tax, tax recycling and emissions

A CO_2 tax is a central parameter for both the fuel choice in the energy model as well as for the majority of the analyses that have been conducted with the linked Hybris model. The tax is levied on the supply of fuels to domestic uses. No differentiation of the tax between uses and sectors is possible and the tax is not levied directly on each sector energy input as is the case for other energy taxes in the ADAM model.

The CO_2 tax is in DKK per ton of CO_2 and is levied on the four fuels in the energy model and then transferred to ADAM. All fuels are taxed according to the CO_2 content of the fuel with coefficients as shown in Table 3. The energy taxes of ADAM also contain a small existing CO_2 tax, so the CO_2 tax levied in the energy model is not a total CO_2 tax and it is not possible to project sector-wise CO_2 taxes following the stepwise implementation laid out in existing Danish legislation.

The CO_2 tax is a key instrument in the energy model inducing fuel substitution but also with large effects on prices for electricity, heat and natural gas. Through these prices and the fuels used directly in other ADAM sectors the economy is influenced by the tax. Apart from fuels in the *ne* sector the tax is levied on the energy import components and thereby it affects prices *pm3r, pm3k og pm3q*. One option for a tax on imports is to use ADAM import tariffs as a CO_2 tax. Hereby the tax revenue can be directly identified[14]. In general the tax is levied on the domestic supply of fuels.

The variables *tm3r, tm3k og tm3q* in ADAM are used for this purpose. In the actual implementation crude oil is not taxed as this import only serves as input in domestic refining and the export from domestic refining should not be taxed. On the other hand the domestic use of extraction production (natural gas) and domestic use of domestically refined products need to be taxed. This is done by using tax variables *tvene* and *tveng*, where the first is used for the natural gas input for electricity and heat production and also the natural gas input in natural gas distribution and the second is used for the refined products that are domestically used. Natural gas has a specific emission and for domestic refined products the average in Table 3 is used. Import tariffs are determined in the energy model as tax per. GJ relative to fuel price without the tariff and multiplied by the ADAM price index for this fuel (import) component,

$$tm3r_t = \frac{råolieafgift_t}{råoliepris_t} pm3r_t \qquad (65)$$

$$tm3k_t = \frac{kulafgift_t}{kulpris_t} pm3k_t \qquad (66)$$

$$tm3q_t = \frac{olieproduktafgift_t}{fuelpris_t} pm3q_t \qquad (67)$$

The tax on refined products, both imported and domestically produced, must take account of lower average emissions than for fuel oil. Therefore the average of emissions in Table 3 is used. Thus, the tax on fuel input used in the *ne*-sector is higher than the tax levied on other domestic users of refined oil products. Taxes on the *ne* sector fuel input are included directly in all calculations in the energy model, but total revenues are calculated based on ADAM variables and therefore the tax has to be levied on the supply of inputs to the *ne*-sector that is not already taxed through import tariffs. Coal imports and imports of refined products already include the tax, but this is not the case for the deliverance from domestic refineries

[14] There is a minor problem with the revenues of import tariffs as a share of these is transferred to EU for which no adjustment has been made. A minor share of CO_2 tax is transferred to EU in this tax implementation.

and domestic extraction activities (natural gas). The tax on domestically refined products is levied directly on the refinery sector ands the tax on the *ne* sector therefore only consists of natural gas taxes.

$$tvene_t = tvene_{93} + \frac{emisgas_t \; CO_2afg_t}{fvene_t} \qquad (68)$$

The total emission from natural gas input is in ton CO_2 *emisgas* and *CO2afg* is the tax per ton of CO_2.

Refineries *(ng)* has input from domestic extraction *e* in the form of crude oil. This input is not taxed and therefore the output of refineries is taxed by *tveng*.

$$tveng_t = tveng_{93} + \frac{emisng_t \; CO_2afg}{fveng_t} \qquad (69)$$

Emission *emisng* is calculated as the domestically used share of refinery output *fxng,* with fuel consumption calculated as

$$Brændselng = \frac{(fxng - ange3\,fe3)}{TJ\ per\ DKK\ \ fixed\ prices} \qquad (70)$$

The tax that is levied on *ne* sector fuel input is reflected in the output price. But it is only the domestic supply of *ne* output and not export (electricity) that should be taxed. Therefore, the export price *pe3* that includes electricity should be adjusted but the electricity export will if it is projected at average historical levels be marginal relative to total energy export *fe3* and therefore this adjustment is excluded. Contrary to this the problem with the export price for refined products needs to be accounted for. The tax levied on domestic refining results in the problem of having two output prices for refined products, one for export and one for domestic use where ADAM has one price only. CO_2 tax revenues are calculated based on *tveng* and this variable cannot be used for raising the domestic price relative to the output price corresponding to taxing only domestic uses. The average export price for energy goods *pe3* has to be adjusted for this fact but it is not possible to adjust the domestic price upwards. The export price is adjusted by the ADAM exogenous correction factor *kpe3*.

$$kpe3_t = kpe3_{t-1}\left(1-(ange3_t + am3qe3_t)\;\frac{tm3q_t - tm3q_{t-1}}{pm3q_{t-1} + tm3q_{t-1}}\right) \qquad (71)$$

Revenue recycling

There are two aspects of revenue recycling. First tax revenue has to be a revenue on public accounts. Next, the choice of recycling principle must be chosen.

The tax revenue from import tariffs in ADAM is partly transferred to EU and this component of public revenue has not been separately addressed in the model and thus public revenues from a CO_2 tax are too low. The tax revenue that comes through ADAM *tve* variables is directly included in public accounts.

Tax revenues are recycled to producing sectors by reducing corporate income taxation. The model is very flexible with respect to analysing other ways of recycling or omitting recycling at all. Also the very commonly used option for recycling by reducing indirect labour costs can be analysed. The macroeconomic consequences of a CO_2 tax are depending very much on the principle for revenue recycling, but the effect of linking energy models and ADAM depends relatively less on the recycling principle.

The tax revenue is recycled by using the total tax revenue calculated from total fuel consumption for each type in TJ and the tax per ton of CO_2. Recycling to ADAM is implemented by using the adjustment parameter *jsdsr* (with negative sign) in the ADAM specification for corporate income taxes shown below.

$$sdsr_t = \left(ksdsr2\ tsds\left(yrs1_{t-1} + tipps_{t-1} - \frac{(ipv4_{t-1} - ipv4bk_{t-1} + ipv4_{t-2} - ipv4bk_{t-2})}{2} \right) + 3751.73\ (d8593_t) + jsdsr_t \right) \quad (72)$$
$$(1 - dsdsr_t) + dsdsr_t\ zsdsr_t$$

This only reduces corporate tax revenues and results in no behavioural adjustment in the producing sector. This effect is connected with investments that are depending on the expected future corporate income tax *tsdsu* that is determined in ADAM by the following relation.

$$tsdsu = (tsds + jtsdsu)(1 - dtsdsu) + dtsdsu\ ztsdsu \quad (73)$$

After a couple of iterations between the energy models and ADAM the following adjustment parameter will have a stable value,

$$jtsdsu = \frac{jsdsr}{sds - jsdsr}\ tsds \quad (74)$$

CO_2 emissions

With the fuel demand found in the energy model it is possible to calculate CO_2 emissions from the two sectors producing electricity and heat. The natural gas distribution sector is assumed to have no emission and all emission that is occurring during transport is thus referred to the final demand.

For the rest of the economy there is not the same detail regarding fuels used and an economy-wide calculation of emissions will have to be based on a number of assumptions.

Emission in the *ne* sector is calculated for each fuel: coal, natural gas, fuel oil, and refined oil products on average. Calculations also give emissions for each category of production: electricity, CHP heat and district heating. Coefficients are given in the table below.

Table 3 CO_2 emission coefficients

Coal	Natural gas	Fuel oil	Refined products on average
95 ton. per TJ	56.9 ton. per. TJ	78 ton. per. TJ	70 ton. per. TJ

It is assumed that the fuel used for electricity and heat production is fuel oil and that biomass is neutral with respect to CO_2 emissions. Only emissions directly from fuel use are included and no transport fuel use is included.

Total CO_2 emissions for the economy are calculated from the supply side. Imports and domestic supply of fuels are used for the calculation corresponding to the description of CO_2 tax above. Fuel categories are coal, natural gas from domestic extraction, imported refined products and domestically refined oil products. Coal consumption is calculated as imports in ADAM (*fm3k*) and is converted to TJ by the 1980 price on coal imports of 10.64 kr. per GJ. This price is marginally higher than the price used for fixed price conversion of coal input in electricity and heat production because the import to other uses had a higher price in 1980[15]. Imports of refined oil products *fm3q* are converted by a price of 40 kr. per GJ, which is the mean of the price for different refined products in 1980. Refinery supply for domestic use is converted with the same price 40 kr. per. GJ, as the composition on different types of refined products is assumed to be the same as for the imported refined products *fm3q*. The domestic deliverance is calculated as

$$fxng_{DK} = fxng - ange3\ \ fe3 \qquad (75)$$

Natural gas consumption is calculated based on data from the energy model and from ADAM. From the energy model the natural gas input in electricity and heat production is calculated. Final demand for natural gas was calculated from ADAM by splitting *ne* sector demand. This demand component also includes *neg* sector natural gas input in heat production. To avoid double counting the natural gas consumption of district heating plants is deducted as it is assumed that only this category of heat production uses distributed natural gas. This assumption is also reflected in the coefficients *anegne* and hereby *anene* that are transferred to ADAM.

By the simple emission calculation for the entire economy-wide emissions some detail has been omitted. Emissions associated with refining are not included and there is no account of change of stocks of fuels that can be large especially for coal. Further no account is taken for re-export of fuels. Emissions are not climate adjusted, but in projections the emissions are depending on *fros* "days with freezing" an ADAM variable that is projected with a historical average corresponding to an average year and is included in many of the demand components determined in ADAM.

5.10 Energy efficiency in ADAM producing sectors and adjustment of electricity export

For 15 of the ADAM producing sectors the March 1995 version of ADAM has introduced an efficiency trend for energy use. This trend can be exogenously projected and transferred to ADAM based on the ADAM base year (1993) efficiency for each of the sectors. Only an average efficiency improvement for all sectors is projected corresponding to an exogenous AEEI. This average projection differs from the very diverging pattern for efficiency trends that can be observed historically. The energy efficiency in manufacturing of fabricated metal products is for example projected by an annual improvement of *AEEI.*

$$dtfvenm_t = dtfvenm_{t-1}\,(1 + AEEI) \qquad (76)$$

[15] It includes imports for residential use in 1980, which is mainly coke.

Finally, a correction of electricity exports is carried out. It is assumed that exports from the *ne* sector are exclusively electricity. Heat is not exported and a possible natural gas export will be directly from the extraction sector. Electricity exports are kept unchanged at an exogenous level in fixed prices (corresponding to fixed size in GWh). This is necessary also to secure that the capacity for electricity production is sufficient to produce total demand as the system is only dimensioned according to domestic electricity demand. If the total energy exports *fe3* grow fast[16] an unchanged export coefficient *anee3* could result in fast growth of electricity exports too. The coefficient is therefore adjusted.

$$anee3_t = \frac{anee3_{93}\, fe3_{93}}{fe3_t} \qquad (77)$$

6. Multiplicators, sensitivity and model critique

To illustrate some of the properties of the model of electricity, heat and natural gas a number of multiplicator exercises have been conducted. These fall in three categories: response to final demand change, response to fuel price changes and response to a CO_2 tax. All these multiplicators are for the isolated energy model described above without the linkages to ADAM that are included in all the analyses reported in the first five papers in the dissertation.

For the separate energy model the importance of incorporating a duration curve and fuel substitution has been examined. The total fuel consumption and fuel mix can be relatively well predicted by using the simple version, but only if there are no major changes of exogenous variables. If relative fuel prices change substantially or demand varies much, then only the model including the duration curve and fuel substitution can be used in a meaningful way.

Total prediction properties of the model has been examined for the years 1990-1997 with regard to total fuel demand and demand for coal.

Multiplicators for the energy model without linkage to ADAM

For the energy model with fuel substitution and duration curve a range of multiplicators have been constructed. The effect of changes in demand for *fxne* production (electricity, heat and natural gas), absolute and relative fuel price changes as well as a CO_2 tax are analysed.

One special property of the model is that multiplicators will be dependent on the base case scenario. Especially the fuel substitution options and composition of the central electricity production system will be important for the size of fuel price and CO_2 tax multiplicators.[17] Also the base case fuel prices and production levels (capacity utilisation) will have an influence on multiplicator experiments.

Only the direct impact in the energy model is included in multiplicators, and therefore, for example price setting (*pxne*) does not include effects through change in

[16] This is very likely as crude oil production and natural gas production grow faster than domestic demand.

[17] This is seen in the paper "Modelling a sector undergoing structural change", section 6.

employment that is determined in ADAM. This is modified in the multiplicator experiments by letting employment follow the development in power capacity.

The experiments have been conducted for plant sizes of 400 MW for new capacity, as this is the default based on the average size of recent plants, but also in some cases with plant size of 100 MW. The change in expansion plant size does only give marginal impacts on multiplicators. The effect can be seen for investment variables and the electricity price.

Change in demand (production).

Multiplicators are different depending on which of the three sub-sector demands that are changed. For the aggregate price *pxne* the largest effect comes from change in heat demand, as the fixed cost component is largest in this sector. Average heat production costs will thus be decreased relatively much if heat production is increased and increased if production is reduced. Heat prices are determined solely by the average costs just as for electricity. For electricity that has large fixed costs also, the price response is less than for heat but greater than for the natural gas price, which is unaffected by demand changes. Natural gas also has large fixed costs, but the model assumes that gas prices are following international gas prices.

For change in the total demand variable (*fxne*) the sub-components of demand are all changed including the dimensioning variable, namely the domestic electricity demand. These multiplicators are given in table 1.1[18].

Table 1.1 Reaction of price (*pxne*) to demand changes (*fxne*)

	1 year	5 year	10 year	25 year
fxne +1%	-0.50%	-0.49%	-0.52%	-0.49%
fxne+5%	-2.42%	-0.97%	-1.91%	-1.80%
fxne+10%	-4.60%	-1.88%	-3.64%	-3.44%
fxne -1%	0.51%	0.50%	0.49%	0.64%
fxne -5%	2.67%	1.02%	2.40%	2.00%
fxne -10%	5.64%	3.86%	3.80%	4.13%
Plant 100 MW fxne + 10%	-4.60%	-1.81%	-4.11%	-3.45%

Table 1.1 shows that a small change in demand of 1% influence *pxne* by -0.5 % and that this is a symmetric response. Larger demand changes tend to decrease the multiplicator and to change the time profile of the multiplicator as a consequence of the impact on expansion of capacity.

A reduction of demand give a somewhat greater effect in raising prices than the decrease of prices accomplished by increasing demand. This is because of the large share of fixed cost in the aggregate *ne* sector. The effect of using plant size of only 100 MW in expansion does not change multiplicators.

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[18] Table numbering restarts in this section. Numbering refers to three categories of multiplicator variables and six key dependent variables in the model.

Table 1.2 Reaction of machine investments (*fimne*) to demand changes

	1 year	5 year	10 year	25 year
fxne +1%	0.00%	0.00%	7.59%	0.00%
fxne+5%	0.00%	4.77%	0.00%	0.00%
fxne+10%	0.00%	13.12%	0.00%	0.00%
fxne -1%	0.00%	0.00%	0.00%	-21.33%
fxne -5%	0.00%	0.00%	-9.26%	0.00%
fxne -10%	0.00%	0.00%	-28.93%	0.00%
Plant 100 MW fxne + 10%	0.00%	10.73%	7.28%	0.00%

Machine investments (table 1.2) are mainly affected by demand changes through the building of large plants that boost investments in the years ahead of the introduction of an additional plant relative to the base case[19]. The impact in time varies and no general conclusion for the size of a multiplicator can be drawn. The larger the demand changes the earlier the investment reaction, also as a consequence of revising expansion planning.

Investment time path is depending on the size of new plants as smaller plant size spreads the investment reaction in more years and hereby decreases the reaction in specific years.

Fuel consumption is changed almost in line with demand changes (table 1.3). This is caused by more than proportional increase in fuel consumption for electricity production and less than proportional reaction for fuel to heat production. Natural gas input is equivalent to output. Heat fuel consumption is increased less than proportionally because marginal demand is assumed produced as high-efficient central CHP where only a minor share of fuel is referred to heat.

Table 1.3 Total fuel input (*fvene*) reaction to demand changes

	1 year	5 year	10 year	25 year
fxne +1%	0.95%	0.94%	1.02%	0.84%
fxne+5%	4.78%	4.71%	3.99%	4.19%
fxne+10%	9.59%	9.45%	8.08%	8.38%
fxne -1%	-0.95%	-0.94%	-1.00%	-0.85%
fxne -5%	-4.76%	-4.70%	-4.80%	-4.17%
fxne -10%	-9.51%	-9.39%	-9.41%	-8.33%
Plant 100 MW fxne + 10%	9.59%	9.45%	8.53%	8.37%

In the longer run the fuel consumption is affected by demand-induced expansion that increases average efficiency and moderate the fuel increase for electricity production. A reduction of demand reduce fuel consumption a little less than demand and in the longer run postponed or cancelled expansion reduces the growth in average efficiency, that is included in the reference case.

[19] More often it is only an earlier introduction of a plant and not an additional 400 MW plant.

Fuel consumption composition is also affected by demand changes as shown in Table 1.4 where the coal coefficient shows positive correlation with demand changes. This is because central CHP plants produce the marginal electricity and heat and because these plants mainly use coal (for new plants with reference case fuel prices **only** coal). Fuel consumption on decentral CHP is not affected as this production category is exogenous. Production in district heating is affected[20] and using the exogenous and constant fuel composition in this category therefore changes all fuels equally. However, the district heat is a decreasing production category in the reference case and the change of fuel composition in large CHP therefore dominates total fuel composition.

Table 1.4 Coal input coefficient (*am3kne*) reaction to demand changes

	1 year	5 year	10 year	25 year
fxne +1%	0.17%	0.24%	0.21%	0.54%
fxne+5%	0.80%	1.15%	0.04%	2.69%
fxne+10%	1.59%	2.19%	0.02%	5.10%
fxne -1%	-0.17%	-0.24%	-0.25%	-0.62%
fxne -5%	-0.89%	-1.23%	-1.59%	-2.84%
fxne -10%	-1.86%	-2.57%	-3.44%	-5.99%
Plant 100 MW fxne + 10%	1.59%	2.19%	0.57%	5.07%

The coal coefficient is affected more in the long run because the base case contains coal-based production as a smaller share in the long run than in the first years. The decrease in coal coefficient in table 1.4 as a consequence of demand reduction is larger than the corresponding increase induced by increased demand.

Emission of CO_2 in table 1.5 is increased a bit more than the fuel consumption because the coal share is increased when production is increased. This effect is symmetric except for the 10-year horizon where there is a difference induced by difference in expansion, just like what can be observed for fuel consumption.

Table 1.5 CO2 emission reaction to demand changes

	1 year	5 year	10 year	25 year
fxne +1%	1.12%	1.16%	1.17%	1.28%
fxne+5%	5.59%	5.81%	4.60%	6.45%
fxne+10%	11.25%	11.64%	9.19%	12.88%
fxne -1%	-1.12%	-1.16%	-1.18%	-1.34%
fxne -5%	-5.58%	-5.78%	-6.05%	-6.35%
fxne -10%	-11.14%	-11.53%	-12.08%	-12.70%
Plant 100 MW fxne + 10%	11.25%	11.64%	9.85%	12.84%

Finally for demand changes table 1.6 shows the results for electricity price that is the most interesting part of the price response. If this table is compared to table 1.1 the price

[20] Heat demand is distributed on CHP and district heat with constant shares. The share of district heating is projected to change over time, but it is fixed within a given year.

response of electricity is less than for the aggregate price *pxne*. The electricity price will, when capacity expansion is necessary, increase until the new plant is introduced (and paid for) but later the new plant efficiency increase will tend to decrease the electricity price. Greater demand changes than 1% reduce the multiplicator on electricity price.

Table 1.6 Electricity price reaction to demand changes

	1 year	5 year	10 year	25 year
fxne +1%	-0.49%	-0.49%	-0.55%	-0.49%
fxne+5%	-2.37%	0.78%	-1.19%	-0.83%
fxne+10%	-4.50%	1.40%	-2.25%	-1.58%
fxne -1%	0.50%	0.49%	0.47%	0.89%
fxne -5%	2.61%	-0.96%	2.04%	0.93%
fxne -10%	5.53%	1.70%	1.36%	1.71%
Plant 100 MW fxne + 10%	-4.50%	1.63%	-3.38%	-1.61%

Fuel prices

Relative fuel price changes affect only fuel consumption on central plants and does not affect expansion of capacity. Fuel mix is affected in two ways as some plants can substitute among fuels and the production allocation for the individual plant according to the placement on the duration curve can change the average fuel composition.

An absolute (uniform) price change on fuels has no effect on fuel composition or fuel consumption. For output prices the reaction is for natural gas the same change, for electricity 1/5 of the change and for the heat price only 1/10 of the fuel price change corresponding to the cost share of the fuel input.

Table 2.1 Reaction of price (*pxne*) to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10%	3.69%	3.80%	3.86%	4.13%
coal price + 100%	9.15%	7.31%	7.18%	4.00%
fuel oil -25%	-0.26%	-0.26%	-0.27%	-0.33%
natural gas -25%	-5.93%	-6.52%	-6.83%	-8.30%
biomass -25%	-0.37%	-0.37%	-0.37%	-0.44%

In table 2.1 *pxne* is increasing by 40% of the increase in fuel prices and increasing in time, as the base case include a rise in the fuel cost share.

The relative price of coal is a central parameter to the model. A doubling of coal prices result in a substantial substitution in electricity production fuel, which again is reflected in the impact on the aggregate output price *pxne* in table 2.1.

The immediate price effect is the largest, but after 10 years when the new multi-fuel plants have been introduced and the maximum biomass share is being exploited the increased substitution mitigates the cost increase of coal. Immediately there exist substitution towards fuel oil and after five years a new gas plant is introduced gradually reducing the price effect.

Table 2.2 Reaction of machine investments (*fimne*) to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10% coal price + 100% fuel oil -25% natural gas -25% biomass -25%	**all zero**			

As the multiplicators are without demand response to price change no change in expansion and investment take place. Therefore all multiplicators in table 2.2 are zero.

Table 2.3 Total fuel input (*fvene*) reaction to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10%	0.00%	0.00%	0.00%	0.00%
coal price + 100%	40.97%	36.74%	34.00%	6.62%
fuel oil -25%	0.01%	0.01%	0.01%	0.00%
natural gas -25%	4.40%	2.18%	0.30%	0.00%
biomass -25%	0.00%	0.00%	0.00%	0.00%

The rise in coal price affects fuel consumption considerably as reflected in table 2.3 that illustrates an immediate sharp rise in fuel consumption caused by a shift towards old and inefficient fuel oil based plants that are not operating at all in the base case. In the long run there is only a minor effect on fuel consumption as it will be the same plants that are running as in the base case with the same efficiency but with another fuel mix. Only the use of the gas-fired plants is different from the base case.

Table 2.4 Coal input coefficient (*am3kne*) reaction to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10%	0.00%	0.00%	0.00%	0.00%
coal price + 100%	-90.37%	-88.96%	-87.57%	-37.60%
fuel oil -25%	-0.05%	-0.03%	-0.04%	0.00%
natural gas -25%	-7.30%	-3.93%	-0.77%	0.00%
biomass -25%	0.00%	0.00%	0.00%	0.00%

The coal coefficient shows the substitution away from coal to the technical limits. At a point in time after 10 years the coal and fuel oil prices are crossing again so that coal is still used in its minimum share together with biomass on the new multi-fuel plants.

The reduction of CO_2 emission from an increased coal price in table 2.5 is substantial and caused by the substitution towards fuel oil and natural gas in the short run and towards biomass in the long run. The resulting increase in the electricity price in table

2.6 is less than can be observed for the 150 DKK CO_2 tax analysed in table 3.6 until 25 years and at the same time emissions are reduced more[21].

Table 2.5 CO2 emission reaction to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10%	0.00%	0.00%	0.00%	0.00%
coal price + 100%	-14.85%	-17.94%	-17.81%	-29.43%
fuel oil -25%	-0.02%	-0.01%	-0.02%	0.00%
natural gas -25%	-3.39%	-1.82%	-0.39%	0.00%
biomass -25%	0.00%	0.00%	0.00%	0.00%

Table 2.6 Electricity price reaction to fuel price changes

	1 year	5 year	10 year	25 year
All fuel prices +10%	2.32%	2.28%	2.28%	1.99%
coal price + 100%	17.43%	14.71%	15.13%	9.47%
fuel oil -25%	-0.33%	-0.36%	-0.40%	-0.51%
natural gas –25%	-0.19%	-0.29%	-0.35%	-0.84%
biomass -25%	-0.20%	-0.26%	-0.33%	-0.54%

For the experiments with other fuel prices (table 2.1 –table 2.6) decreasing their relative price by 25% has limited effect on substitution and fuel composition, only natural gas is used to a greater extent in the first years. The gas price has the largest effect on *pxne* (6%-8%), but this is caused only by the large share of the natural gas distribution sector in the aggregate *pxne* price.

Small changes in relative fuel prices have only minor effects and this will be the same for the corresponding increases of the three fuel prices.

CO_2 taxes

The multiplicators for CO_2 taxes are very much like the increase in coal prices as a CO_2 tax implies a rise in the relative price of coal. It is however here important that these experiments include no recycling of CO_2 tax revenues, which can affect fuel mix, emissions and prices considerably as for example in the paper on recycling to subsidise biomass use.

Table 3.1 Reaction of price (*pxne*) to CO2 taxes

	1 year	5 year	10 year	25 year
CO2 100 kr.	16.63%	14.42%	11.95%	6.10%
CO2 150 kr.	24.95%	21.44%	17.80%	9.08%

The price rise is proportional to the CO_2 tax but the effect is reduced over time. The reduced multiplicator is a result of the CO_2 tax being in current prices and the baseline including substantial increase in energy prices. It can be observed that the highest CO_2

[21] The two experiments cannot be directly compared as fuel price changes are exogenous and the CO_2 tax includes no recycling.

tax even though it induces long-term fuel substitution, which the 100 kr. tax does not, has nearly the same price effect.

Table 3.2 Reaction of machine investments (*fimne*) to CO2 taxes

	1 year	5 year	10 year	25 year
CO2 100 kr.	0%	0%	0%	0%
CO2 150 kr.	0%	0%	0%	0%

Machine investments like for fuel prices do not respond to CO_2 taxes. This will be very much in contrast to what happens for investment if the demand response in ADAM was also considered.

Table 3.3 Total fuel input (*fvene*) reaction to CO2 tax

	1 year	5 year	10 year	25 year
CO2 100 kr.	0.01%	5.05%	0.95%	-0.36%
CO2 150 kr.	0.02%	6.22%	5.76%	6.62%

The substitution profile of a CO_2 tax is reflected in table 3.3. First in a 5 year horizon coal is substituted with fuel oil on plants that are less efficient, which result in total fuel input rising. This effect remains throughout the period for the 150 kr. tax, but for the tax of 100 kr. the prices including tax of coal and fuel oil are crossing again so that from 10 years coal regains most of the share.

Table 3.4 Coal input coefficient (*am3kne*) reaction to $_{CO2}$ taxes

	1 year	5 year	10 year	25 year
CO2 100 kr.	-0.05%	-8.39%	-2.06%	-1.88%
CO2 150 kr.	-0.06%	-10.93%	-11.29%	-37.60%

For coal the substitution first result in a reduction of coal use which for the 150 kr tax is increased as biomass introduced in new plants after 10 year gradually substitute coal. Therefore the tax of 100 kr. is insufficient to induce the long-term substitution reducing CO_2 emission that is the goal of the tax. The long-term reduction is achieved only when considering a CO_2 tax of 150 kr. It must be noted that the reduction for 100 kr. is established by substituting coal with natural gas and if the expansion technology in the baseline had been natural gas the 100 kr. tax would have resulted in a greater emission reduction than in table 3.5.

Table 3.5 CO2 emission reaction to CO2 taxes

	1 year	5 year	10 year	25 year
CO2 100 kr.	-0.02%	-3.82%	-1.00%	-1.50%
CO2 150 kr.	-0.03%	-5.48%	-5.69%	-29.43%

Table 3.6 Electricity price reaction to CO2 taxes

	1 year	5 year	10 year	25 year
CO2 100 kr.	18.06%	15.01%	12.61%	5.51%
CO2 150 kr.	27.10%	22.14%	18.63%	8.08%

Electricity prices are influenced by the CO_2 tax in a similar way as the aggregated price *pxne.* In the long-term the price impact is a little less as the possibility for substitution in electricity production fuel use decrease the tax impact. In the short run the impact on price is a little larger than for the aggregate price as a consequence of less flexibility of fuel choice in the existing system and more CO_2 content in the electricity fuel than for average input in the *ne* sector.

Comparing the electricity production model with and without fuel substitution

The use of a duration curve and fuel substitution options for central power plants has been compared to a simpler version based on average fuels and average efficiencies. The comparison is carried out with respect to fuel consumption and only for the years 1990-1994.

In the simple version two categories of central plants are included: old existing plants and new capacity. Both categories are assumed to be CHP and production of electricity is distributed evenly on the different fuel technologies. The full load hours for new and old plants are different and specified exogenously. The simple version implies that parameters, Cm, Cv, efficiencies etc. are calibrated for the two categories to 19909 data. The comparison results in a large difference for the use of fuels for heat production, where the version with duration curve etc. has higher efficiency for heat production. This results in around 20% less fuel consumption for heat relative to the simple version and actual figures. There is large excess capacity for heat and only the most efficient CHP plants produce heat in the fuel cost minimising version. In reality there are restrictions for geographical location of heat demands and restrictions from duration of heat demands. This is more in line with the average production for the categories of old and new plants in the simple version. Only the introduction of minimum heat production for each individual plant, that is a possibility in the cost minimising model, can produce more realistic fuel consumption for heat on central plants. With respect to fuel consumption for electricity the difference in fuel consumption is small. The comparison of the two versions is only valid for relative fuel prices close to those prevailing 1990-1994.

The really important difference between the two versions is found when it comes to analysing taxes and fuel price changes. Only the model version with the duration curve and fuel cost minimisation (substitution) can handle such analyses. Therefore, it must be concluded that for policy analyses including fuel price changes the cost minimisation model must be preferred.

Fuel demand projection properties

The projection of fuel input for electricity production based on a given level of demand is compared to actual fuel input in Figure 5. Only fuel consumed in utility owned facilities are included. Two observations can be made.

- The model underestimate total fuel use in all years.

- The declining share of coal is not reflected in the projection.

There are two main reasons for the underestimation of total fuel consumption.

- The model does not include stop and start related fuel consumption. Basic efficiency parameters for individual plants are used only.
- The heat restriction associated with the obligation to meet the local heat demands implies that it is not always the most efficient plants that are operating.

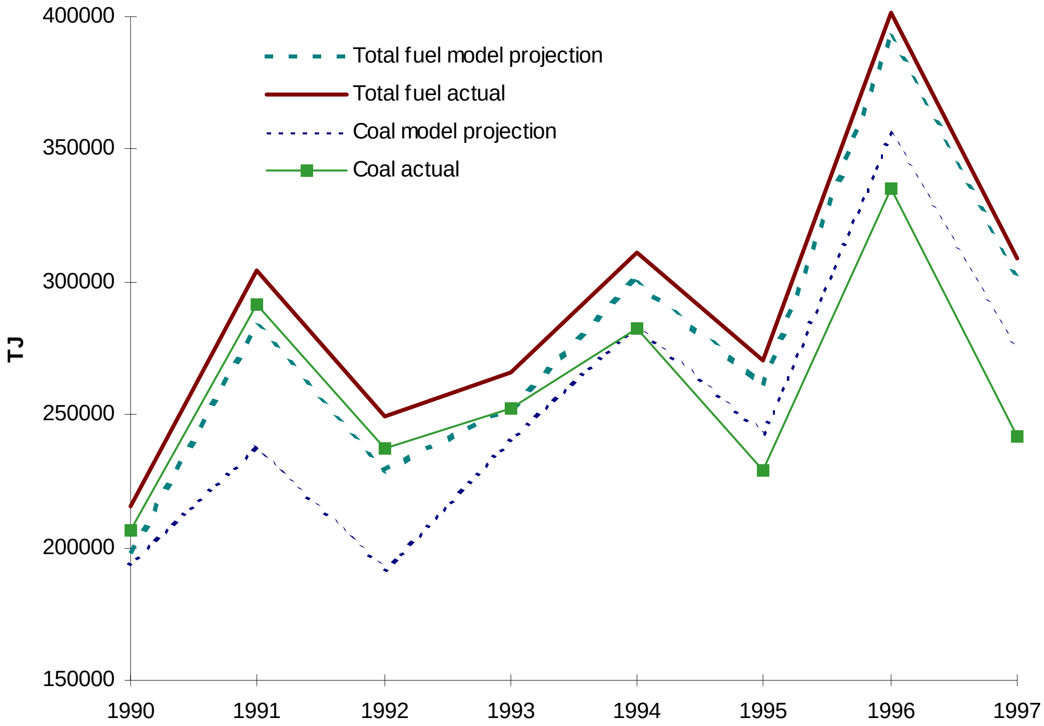

Figure 5 Model projection properties for fuel consumption in electricity production

Regarding the inability to predict the decreasing coal share in the illustrated period also two factors are important.

- The agreements concerning natural gas use require that gas be used independently of its competitiveness. The restriction concerning local heat demands also influence the choice between natural gas fired and coal fired plants. Two little natural gas demand is projected.
- The use of orimulsion is not accounted for in the model and especially for 1996 and 1997 this fuel was used to some extent.

Electricity market restructuring - liberalisation

The model for electricity and heat production is based on the until today prevailing regulatory regime of this sector in Denmark. Changes from this have taken place in recent years and more changes are on the way. Producers of electricity are now competing both domestically and abroad about the electricity purchase from large industrial customers. A new legislation for the electricity producing sector implies that both tradable CO_2 emission quotas and markets for green certificates will be introduced. Has this situation influenced the usefulness and realism of the model? To some degree yes. There are a number of critical aspects of the Hybris model that can be commented in the light of the new developments.

- Fuel consumption and fuel mix
- Price setting
- Expansion
  - Technology
  - Timing
- Duration of electricity demand
- Imports – connection to other markets
- Linking with ADAM
- Policy analyses
- New policy instruments

Fuel consumption for a given level of Danish production will not change much as a consequence of liberalisation. What could change is the level of Danish production. The plants with the lowest marginal costs will still be the plants producing and the restrictions related to local heat demands will also continue to influence the fuel consumption. Fuel mix on the individual plants will be determined in the same way as previously. The model properties that allow analysing the combination of regulated technology and unregulated fuel and production choices are still valid in the liberalised regime. Marginal production costs will probably not change very much as fuel costs and the main technical characteristics of the existing system will remain unchanged for many years.

Heat prices could make a difference. If these are determined independent of the electricity production the minimisation of joint costs will not be valid. The minimisation with one given heat price will still be valid, but this will not necessarily produce the demanded heat. The output decision is endogenous to a larger extent. In practise the heat demands will be met, but heat prices will probably be negotiated (and increased) locally, reflecting that a larger share of the CHP efficiency gain is referred to electricity.

Another reason that the model properties for fuel consumption are still realistic is the fact that the majority of exogenous production categories are treated as prioritised production in the new legislation that liberalise the electricity market. This implies that the exogenous production categories also in the liberalised market contribute to demand by an exogenous production and exogenous fuel mix. The share of production from these categories will contribute by a share rising from around 30% to around 40% in 10-15 years.

Price setting will be a much more complicated issue in the liberalised regime and Hybris is not capable of describing the price setting and its dependence on market power, connection to foreign markets and strategic behaviour. Prices will probably vary to a much larger extent than today among different consumer groups and over time. The Hybris model assumes one uniform price independent of the sector demanding the energy[22]. The input price in the different sectors in ADAM only varies due to different taxes and different wholesale profits. To include different basic energy prices for final demand in Hybris the wholesale profits in ADAM energy price specifications can be used, but thus the wholesale profit will not be attributed to the electricity, heat and natural gas sectors (*ne*) but to the trade sector. The foreign competition will also increase very much its importance for price setting in the Danish market. The price setting will in many respects be much more complicated than today and market power resulting from a reorganisation that not decentralises power can produce even more complex price structures.

Expansion technology will not continue as a mechanical reserve capacity restriction as it is described in Hybris with an exogenous expansion technology. Expansion technology in the liberalised regime might be changed due to higher risk and expansion will probably be much more limited than until now. The technologies with highest capital cost and the least fuel costs will probably be seen as less favourable than today. Consumers won't finance expansion the way they have done until now and external financing will probably be limited due to risk and the unsettled organisational issues. But the regulation of technology will continue, for example approvals of new expansion still have to meet some criteria. However, the most likely result is that the technology regulation will be less restrictive than until now.

The timing of expansion will be influenced by the liberalised regime. The increased uncertainty in general and especially the organisational and financing situation will limit expansion. There is large excess capacity in Denmark today and there will probably not be any expansion with large plants apart from the ones currently underway. What will probably also happen is that some of the oldest capacity will be definitely scrapped as a consequence of a reorganisation. Secondary capacity will continue to grow if the market for green certificates will be functioning in the way it is intended, but the pace of growth will be slower than in recent years. The Hybris description of expansion that take place around 2015 and hereafter including the resulting investments and investment related price changes will not be a realistic description in a liberalised regime.

The duration curve for demand for electricity is one of the major assumptions in the model. It is assumed that the total demand profile captured in the duration curve is determined solely by domestic demand. The assumption of a constant shape of the duration curve for demand is more critical the larger the transmission capacities and integration with the Nordic market become. The shape of the duration curve will be affected by the time profile of the export demand. A more widespread use of differentiated time tariffs induced by competition might also change the shape of the duration curve.

[22] This is a simplification also relative to the practices of the present situation where industrial consumers are paying substantially less than residential consumers partly to reflect higher distribution costs to the residential sector.

Import competition will be a major influence on the Danish electricity and through electricity also the CHP heat market. The model includes an option for import competition but it is only an import capacity and an exogenous and constant import price that establish this. The import capacity will either be fully used or not used at all as the variation of marginal production costs for Danish plants that cover the domestic demand duration curve (in an average demand year) are within a rather narrow band. The exogenous import price will only occasionally be within this band. Danish producer costs will not influence the import price very much at least not when transmission capacities are limited relative to excess capacity (average to wet year) in the Nordic system. In such cases the price will be given in the Nordic market with little influence from Danish demand and thus the exogenous import price is not too unrealistic. However, to some extent the Danish integration with the Nordic market will drive up the Nordic price in wet years and reduce the Nordic price in dry years. From this discussion it is evident that Hybris alone cannot provide insight on the integration with other markets.

Another major issue related to the relative import price and especially important in analysis of CO_2 taxes and environmental friendly electricity production is whether the deteriorated competitive position of Danish production induced by a CO_2 tax or CO_2 quotas can be compensated for by taxing imports of electricity[23].

As the **linking** and integrated analyses options is one of the most important properties of the Hybris model the consequence of the changed electricity market regime for the linking deserves special interest. Linking properties are not changed by the new electricity market regime, and the most important link from fuel taxes to electricity price and final demand response in ADAM is intact, even though the **size** of electricity price response to fuel price changes is more unclear. Liberalisation will most likely reduce other costs than fuel costs and in particular as is already seen today wage costs, where the employment has been considerably reduced both at the large plants and in the distribution. Thereby the importance of fuel price changes will be increased, as they will constitute a larger share of total costs.

The policy instruments that can be used in the liberalised regime are somewhat different from the old regulatory regime. It will be much more difficult to impose a restriction/agreement on the use of a specific fuel as in the biomass agreements with the utilities. On the other hand the regulation of expansion technologies can be continued to some extent. One example is the inclusion of biogas in the market for green certificates, which give producers an incentive to expand this production capacity. The liberalised market with possible transboundary producer constellations will make it harder to regulate expansion, as capacity expansion might well be relocated to other countries just supplying the same market from there if restrictions impose too high costs.

The basic results of the energy model regarding the effect of CO_2 taxes are still realistic regarding the short term effects of fuel substitution within plants but the effects in the longer term perspective will be influenced by the size and timing of expansion that contains the fuel flexibility in the future. As the new capacity in the reference case is

[23] Subsidising exports to compensate for the cost of exceeding CO_2 quotas seems a peculiar and unrealistic option.

introduced mainly in the years after 2013 the medium term properties of fuel mix and substitution options are relatively unaffected by the liberalisation. The CO_2 tax will affect the competitive position against foreign producers unless compensated in a way.

Among the **new policy instruments** the market for green certificates that is contained in the liberalisation are meant to secure future expansion of environmental friendly energy technologies by reducing risk for investors[24] and to secure that owners of this capacity receive a reasonable revenue from their production. But as the Danish system is equipped with serious excess capacity the part of revenue that come from sales in the electricity markets from prioritised production categories will be associated with large uncertainty and total revenues will probably be lower than in previous years. This might result in that not only conventional capacity expansion, but also expansion of capacity for the prioritised categories will be limited for many years under the proposed regulation regime with the given maximum and minimum for the price of green certificates. Unfortunately, the Hybris model is not suited to analyse the green certificates or the connection between markets for green certificates and markets for electricity.

The introduction of tradable CO_2 emission quotas within the power sector is another aspect of the liberalisation. This issue could be incorporated in the model but it is not a feature of the existing Hybris model. It is very unsettled whether the CO_2 quotas planned will be binding for an average year. The quotas will tend to increase marginal costs in low water years[25] and reduce exports these years; or more likely increase the price of exports these years. If the latter is the case the CO_2 tax associated with exceeding the quota will have to be paid by the foreign consumers, which seems a reasonable principle.

For Hybris the conclusion is that the model was designed in 1994-1995 with the linking as the main objective and not to analyse new aspects of energy market development such as liberalised energy markets. The model is basically not suited for analyses of this kind, as analyses of market issues essentially must include a description of the connection with the Nordic and other markets.

7. A critical assessment of the results appearing in the first five papers

The **first paper** surveys a number of different approaches to modelling and characterising technological progress within the energy field. It is also illustrated that two totally different approaches for describing residential energy demand can produce similar demand projections, when a reasonable range of exogenous efficiency improvements are used in the models. Therefore it is just as much the exogenous efficiency assumptions in the models as the approach that lead to different projections.

[24] Risk is reduced relative to operating exclusively in the liberalised market, but increased relative to the previous situation and the favourable conditions that are given for existing wind capacity in a transition period. For new producers taking part in the market for green certificates the effect will be an increase in revenue relative to the basic revenue from electricity production, but there will still be large fluctuations in their total revenue.

[25] As the marginal production will be coal or fuel oil based export

In general some comments about Hybris can be stated in light of the emphasis put on innovation in the first paper.

Innovation is not described in Hybris. The projected increase in efficiency for new vintages of power plants is not endogenous. The AEEI in electric appliances and the general AEEI in ADAM is exogenous and this general AEEI in Hybris includes everything, also diffusion. No policy can increase the autonomous efficiency development for industrial demand for energy. Average efficiency can only be affected by policy in residential electricity demand and for power plants, which is an effect created by increasing the speed of diffusion. Therefore the Hybris model like most other empirical models lacks a sufficient description and explanation of innovation.

The comparison of ADAM and the bottom efficiency projections conclude that the residential energy demand projections depend just as much on efficiency assumptions in the two models as on the different properties of the two models. These are just examples that show how different assumptions in different models can produce projections that are quite close. One way of using these models are to make consistent projection. The top-down model can be used in combination with the bottom-up energy demand to calculate the top-down implied rate of efficiency improvement to generate the same energy demand as in the bottom-up model. Hereby the bottom-up energy demand can be checked for realism with regard to the very detailed efficiency assumptions in the bottom-up model.

The comparison of the two models includes no discussion of the relevance of the description of other driving forces than efficiency. I will leave the basic discussion of vintage models for residential electricity and heating demand to the discussion of the second paper.

The **second paper** is focusing on diffusion of existing technologies. As diffusion is argued to have a substantial impact on energy demand in a short- to medium-term perspective the different possibilities for including diffusion in models and policy options for influencing the speed of diffusion is examined.

Some comments on both the models applied for the illustrative purposes and the results are appropriate.

- The results obtained about efficiency effects of utilisation rates etc.
- Critical aspects of the vintage model for residential electricity demand
  - The model lacks prices for appliances and electricity price effects on the appliances purchased
  - Economic driving forces play a minor role
- Critical aspects of the model for residential heating

In a short to medium term perspective the diffusion of technology is well described in the vintage models of electric appliances and power plants. Here the already known technologies and their efficiencies, fuel composition etc. diffuses through the stock/capital.

One effect that is found in the applied model of electricity and heat production is that there are average efficiency effects of capacity utilisation rates: High utilisation in the power sector decreases average conversion efficiency as utilisation of old inefficient plants are increased. This result cannot be generalised to industrial production where increased capacity utilisation might reduce per unit of output energy consumption. This will be the case if machines in general are used longer time[26]. A capacity effect such as found in the electricity sector model could be found elsewhere if its is the effect of putting old inefficient machines into operation that dominates. There might also be bottlenecks in using specific machines that will reduce overall energy efficiency when utilisation rates are increased.

Prices for the different versions of a given type of appliance are not included in the model and the consumer choice between the different versions is not explained. Diffusion of the relatively more energy efficient technology does not depend on prices. Therefore the model is incapable of addressing the cost of regulation. Policies, both economically and technically based, to increase the speed of diffusion are very much in focus. The vintage model of electric appliances is focusing on the use of standards for increasing the diffusion of the most energy efficient technology available. Economic instruments have very little impact in this model. Price incentives via subsidies for efficient appliances cannot be analysed, as there is no description of consumer behaviour for choosing which version of a given appliance to buy. Electricity prices do not affect the technology choice for the same reason. Thus, in this model economic instruments can only affect energy consumption by decreasing the intensity of use. An indirect option for reducing electricity demand is to tax the purchase of durable consumer goods, which will reduce the penetration growth (the stock) of electricity consuming appliances but also slow down the technology diffusion. Economic instruments to speed up diffusion are relevant to analyse and it is most likely that, for example, subsidies to energy efficient versions of appliances will speed up the diffusion. It is also quite certain that high electricity prices will result in a more efficient mix of purchase and hereby a higher average efficiency. This might be accompanied by a faster replacement of old appliances thus reducing economic lifetime and increasing the speed of diffusion. Such policies will inevitably be associated with costs that also have to be addresses. It is an important limitation for the capabilities of the vintage model that these effects cannot be analysed.

Economic behaviour and **economic driving forces** in the vintage model for residential electricity demand is nearly absent or it is assumed that every thing is equal, for example with respect to the investment costs of different versions of a given appliance. The underlying assumption in the vintage model of electric appliances that saturation levels exist for the individual appliance is a realistic assumption for many appliances. But a general long run saturation level for electric appliances, that is the result produced by the applied model, is certainly contestable. There is no satisfactory description of new electricity consuming appliances in the model and the category of new appliances

[26] Increased use of extra evening or night shifts.

therefore remains a marginal category resulting in the overall saturation for electric appliances in general.

For the **model of residential heating** demand no economic driving forces are included except for the macroeconomically determined investment in new dwelling transformed to a m^2 figure. The model is mainly a projection of local efficiencies. Economic behaviour is relevant as is seen from the dependency of average efficiency improvement on heat input prices. The diffusion of technology certainly seems to be associated with economic conditions. Another relevant issue for economic impact could be to include the widespread use of subsidies that has been seen for insulation, conversion from electric heating etc.

Discussion of results in papers 3-5

The **third paper** about the linking in Hybris "Integrating the bottom-up and top-down approach to energy-economy modelling: The case of Denmark" describes both the linking and illustrates one important property of the linking. The linking established in Hybris and described in the paper can be criticised in a number of areas.

- Linking and integration is limited to the areas of demand were the approaches do not conflict much. The areas chosen for bottom-up energy modelling are the most obvious areas. To integrate bottom-up models for energy demand in manufacturing with bottom-up characteristics as described for heating, cooling, process etc demands separately and associated with potential reductions in each end-use category would have raised other fundamental questions. The main characteristic of Hybris with respect to final energy demand remains that of a top-down model. In these areas the model has not solved the issue of integrating the two approaches.
- Integration could have caused more fundamental problems with other categories of models. The practical integration could have caused more problems in other categories of macroeconomic models especially those that have a description of energy demands integrated in total factor demand specifications.
- There are inconsistencies in Hybris with respect to consumer behaviour for different categories of demand. Finally the mixed integration principle implies that inconsistencies exist with respect to the description of consumer behaviour. Why should consumers not respond to electricity price changes by choosing another mix of electric appliances (more efficient ones) when they respond by using some of the appliances with less intensity?

The link between investment in electricity, heat and natural gas sectors and ADAM plays a minor role in Hybris. Investments in plants are linked to ADAM, but the majority of investments in district heating grids as well as natural gas grids are not described in Hybris. Therefore important aspects of the previous Danish policy of expanding these grids and the interdependence with the CHP production is not covered. Finally it must be noted that ADAM as a demand driven model will exhibit GDP gains from increased investment as in more expensive renewable energy technologies, which offsets some of the GDP loss associated with higher electricity prices.

The analysis of **combined initiatives** to reduction of CO_2 emission implies that it is impossible to attribute CO_2 reduction to a specific instrument in the package. It is only possible to find the marginal reduction effect of an instrument given that other instruments have been implemented or not. As there are large interdependencies between the effects of instruments the marginal reduction effect of one instrument will depend very much on which instruments that are already implemented. Another feature that can be observed is that the larger effects of individual initiatives in the integrated model are caused by price demand - responses.

The technical demand side reduction (option c) in the paper) is independent of taxes, the only interaction effect consist of reduced residential electricity demand for which no fuel switching in the electricity production can take place. Regulating fuel use in large plants are to some extent a substitute to taxing fuel use in these plants, and taxing fuel use can be one solution when moving from a regulated regime to a more liberalised market regime. It will be very difficult and inefficient to regulate fuel use on the individual power plant.

The CO_2 tax instrument a) in the combined initiative analysis induce costs measured as GDP loss but the technical demand side instrument c) is not associated with any costs. This absence of costs from a policy of using standards c) is not realistic, but it must also be noted that GDP in ADAM is not the best measure for these costs. If standards imply higher costs of appliances that are not compensated by reduced electricity consumption the service of the appliance has become more expensive. This might reduce demand for the appliance, but most of this will be compensated by increases in other private consumption categories in ADAM. All in all it is most likely that there will be no GDP loss from higher prices on durable consumer goods. This totally ignores the loss to consumers of a restricted access to buy different versions of a given appliance.

The **fourth paper** is concerned with the issue of recycling CO_2 tax revenues and the impact on the emission reduction and the economy. The question of economic costs of CO_2 taxes has been in focus in so many studies and model exercises. The recycling of tax revenues is central for the results obtained by the macroeconomic models used for this type of analysis. Therefore, recycling options have been compared and analysed and in some cases optimised. But the recycling have been focusing on recycling throughout the economy.

In the paper on recycling the possibility of recycling directly to the use of environment friendly fuels exemplified by biomass is examined. This option is not analysed in many macroeconometric models and the lack of empirical data to estimate elasticities for biomass use in most cases leaves biomass as an exogenous fuel if considered at all. The large substitution options among coal, fuel oil, natural gas and biomass in the Hybris model makes the recycling of tax revenue within this sector an important issue. Recycling as subsidies is compared to recycling by reducing the corporate tax rate. The sectors paying the CO_2 tax are thus not necessarily the same sectors that gain from the reduced tax rate. For the overall economy the corporate tax reduction moderates the contraction effect from the higher input tax that increase production costs. Recycling as subsidies does not imply moderating a contraction effect of taxes but instead it reduce the necessary tax to reach a given reduction target. Private consumers are not directly compensated by reduced corporate taxation so they face higher energy prices without compensation and reduce their energy consumption much more than in the case of subsidising biomass, where the increase of electricity and heat prices are only moderate.

The results in the paper shows that recycling to biomass use reduce the necessary tax to reach a given reduction level considerably compared to a recycling through corporate taxes. The economic costs at least measured by GDP are depending on the level of tax and the reduction of the necessary tax reduces the GDP impact considerably. The existence of fuels that are perfect substitutes as input in electricity and heat production makes it worthwhile considering recycling as subsidies to the fuels with the least emission. The results in the paper are obviously depending on biomass assumptions. These assumptions can be criticised for both economic and technical reasons.

- Biomass supply curve: It is critical that price is assumed independent of supply. The domestic resource of straw is limited and increased volumes require more transport, most pronounced if is used in central plants. Straw as a fuel competes with other uses associated with livestock production or ecological farming. Therefore the costs of biomass will be rising as volumes increase above the basic by-product range and alternative uses exist. The biomass volumes that are in the analyses reported in the recycling paper are probably including straw, that has alternative uses, but the volumes are not beyond the domestic resource of straw, biogas and energy crops on marginal farm-land.
- Recycling of revenue can only keep biomass a competitive fuel as long as the revenue is sufficiently high. The necessary tax to raise revenue will increase with biomass volumes and in the long run situation in the paper revenue is insufficient to extinguish the total substitution options. As coal will always constitute 50% of fuels on the new capacity in the model there will always be revenue to subsidise biomass and the necessary tax will thus always be lower than the tax corresponding to corporate tax recycling.
- Problems associated with biomass concerning its environmental characteristics exist. Biomass (straw) as a fuel has other emissions that can have negative environmental impacts. Even the transport and the storage of biomass will give rise to some CO_2 emission.
- The long-term effect on maintenance costs etc. on the large plants is not considered in this analysis. Substituting coal with biomass might influence efficiency parameters.
- Recycling by lowering corporate tax rates is analysed as a representative traditional recycling principle. Other recycling principles could produce even lower reduction costs than the biomass subsidy. The argument against these "optimal" recycling principles is that any public revenue could be used for such recycling so this is no special feature of the environmental policy.

The **fifth paper** on structural change of the electricity sector illustrates how one kind of structural change namely the technical characteristics of fuel substitution options change the properties of the model or electricity producing system. The substitution options are substantially influenced by regulatory policies both with regard to expansion of technologies without fuel consumption at all and by the restrictions of requiring expansion to be multi-fuel CHP plants. Regulation of technical details for new capacity can have a large impact on fuel substitution options and hereby a large impact on the effect of emission reduction policies based on taxes as is seen in the paper. Substitution elasticities among fuels used in power plants depend very much on regulation. A large share of renewables especially wind will decrease future fuel substitution options for the entire sector. An econometrically based model does not capture the change in substitution options; neither does a general equilibrium model with constant substitution elasticities. A model that incorporates fuel substitution ranges for each plant with a specified lifetime does hereby more adequately describe the future response to fuel taxes. By restricting new capacity to be multi-fuel might impose costs on final consumers (higher investment costs), but this might be seen as an option premium that secure future flexibility for using the CO_2 tax instrument with lower economy-wide costs for a given level of emission reduction. A critical comment to this is that the present policy trend is to leave the investment choice to the producers and this will make the investment decision an economic one taking account of the value of future substitution options in the light of possible future taxation.

The generality for macroeconomic modelling of this importance of changing substitution elasticities induced by regulation is probably limited. Only few cases exist in a macroeconomic model context where two inputs are fully substitutes. If very disaggregated inputs are examined other examples can be found as for example, natural product inputs relative to synthetic alternatives. Also in this case the reduction of the production price of synthetics will eventually at some level result in a total substitution of the natural product in favour of the synthetic product. But if aggregated inputs as different sorts of labour, capital or land are examined the inputs will not be complete substitutes.

There are other structural changes as organisational and regulatory regimes that change also the properties. These are just as important as the kind of structural change examined in the paper. Another structural change for the electricity sector could be the liberalisation of and split of producers that in a situation with massive excess capacity will drive prices from break even pricing towards marginal cost pricing until some capacity reduction or concentration has taken place.

8. Summary of conclusions

The topics covered by this collection of papers was seen as some of the most interesting issues for long-term energy demand in a country like Denmark. There is no single conclusion from the papers regarding the driving forces for energy demand in the long term, but the importance of technological progress and various forms of structural change have been emphasised in the conclusions throughout the dissertation.

Technological progress is a very diversified issue, but certainly one of the most important issues for long-term energy demand. Technological progress consists of invention and innovation of new energy technologies and on the diffusion of these technologies. These two issues are very different both with respect to the possible policy options to influence the rate of progress but also with respect to the kinds of models that describe the two issues. All attempts to model long-term energy demand must include a description of the relationship in which technological progress enters the model. Energy-economy modelling has not been very successful in describing technological progress in a satisfactory way. Especially, the explanation for innovation has been excluded in many of the large empirical models. Only recently attempts have been made to include and endogenise technological progress in the form of innovation in empirical energy-economy models.

As the first paper shows two totally different models for residential energy demand can result in similar demand projections, even though one is based on saturation of energy service needs of households and the other is driven by income and energy prices. The reason is that both models depend crucially on the assumptions that are part of both models with respect to technological progress. This parameter is just as important as the different approaches that characterise the two models and at the same time the size of annual progress is a very unsettled issue.

Diffusion of technology and its speed is important in a short- to medium-term perspective. The paper on diffusion shows how capacity utilisation effects on average fuel efficiency is a property of the electricity and heat production model. As discussed above this cannot be generalised to energy efficiency in other industries, as there are factors with opposite influence. High capacity utilisation might imply using all machinery more intensively, reducing the importance of fixed (start-up) energy consumption and improving average energy efficiency or as in electricity the least efficient machinery has to be put into operation reducing average energy efficiency. The final comment on technological progress is that progress is not constant and certainly not independent of the economic conditions and parameters as is most often the description of energy efficiency in macroeconomic models.

The linking of Danish bottom-up and top-down models was a major achievement for the possibility of carrying out the analyses of combined CO_2 reduction policies and the recycling of CO_2 revenue conducted in two of the papers included here. The benefits of the linking are consistent analyses of changes in the electricity and heat supply sector with the derived final demand consequences of change in output prices. The impact of changing economic conditions can be analysed for the demand and output price consequences in the electricity and heat sector. With regard to very technical emission reduction options as standards these are now possible to analyse in combination with traditional macroeconomic policy instruments as CO_2 taxes. This kind of linking for models based on different approaches can be established for other categories of final energy demand, for example a bottom-up description of the refinery sector could be linked to ADAM without causing major problems or changes in the economic properties. On the other hand a bottom-up description of potential reduction options for end use categories in specific manufacturing industries would be hard to link to ADAM without addressing which of two fundamentally different explanations for energy demand to prefer. The linking has in general preserved the traditional top-down properties and has even increased the effect of prices and especially a CO_2 tax to reduce emission. This is a realistic change of properties relative to ADAM properties as fuel substitution in electricity production is a central issue for all analysis of CO_2 mitigation options. The result that combined reduction initiatives exhibit interaction effects that reduce the total effect of initiatives compared to their individual effect is not very surprising, but it has often been ignored in the debate that compared economic instruments to more technically based regulatory instruments. What is also often ignored is the final demand response to changes in the electricity and heat sector that result in cost and price increases. This effect is captured in the developed model.

The main characteristic of the Hybris model remains that of a top-down model. The most important drivers for final energy demand are fuel prices, production and income. For analyses of energy demand in general it is not a question of using either a bottom-up or a top-down model but more important to use a model that is appropriate for the issue in question. This also means using a linked model for analysing possible interactions, when the focus is on aggregated energy issues or aggregated policy analyses and especially for analyses including a range of policy instruments. In my opinion bottom-up models add a detailed technology description to the top-down model and hereby they characterise the options and restrictions that the agents are facing in their choices that are based on economic behaviour.

Recycling of CO_2 revenues has been examined in many model contexts and this issue has important implications for the macroeconomic costs of CO_2 emission mitigation. Recycling by subsidising a fuel with low or no CO_2 content as biomass can substantially reduce the GDP loss associated with a given reduction target compared to recycling via corporate tax rates.

Structural change of the economy and in specific sectors has been an issue in three papers. The first paper deals with a specific sector and the next two deals with structural change in trade patterns. With specific focus on the sector of power and heat structural change can be analysed in a model that incorporates optimising producers of electricity and heat along with physical constraints and detailed public regulation. In this case structural change can be interpreted also as including the medium term decisions and regulation of the authorities. If the aim is to analyse the energy impact of a possible restructuring of a sector a detailed model like the one in the paper will be needed. This applies to both restructuring that affects the characteristics of the physical production capacity and restructuring that affects market functioning or organisation, for example, the set of incentives on which the producing and price setting is based.

Energy technology and structural change of trade are related in different ways producing both competitive pressures and advantages to the domestic production. In the case of Denmark the evidence of energy intensive industries exhibiting slower growth than less energy intensive industries was very weak. As opposed to this the consequences of the policy of promoting district heating and renewable energy, especially wind power have contributed to a large increase in exports of these products. The change in the energy technology for power production and residential heating has also contributed to a change in the trade figures for energy goods.

Trade patterns can have large impacts on the production structure of a small open economy as the Danish. The expected tendency for trade developments to reduce energy demand in an industrialised and service sector based Denmark could not be found in Danish data. The result from the decomposition analysis was the opposite as trade changes in the period from 1966 to 1992 had increased manufacturing energy consumption by around 10%. The three components of the trade pattern show different effect on various industries. The rising export shares have contributed to rising energy demand in nearly all manufacturing industries, but especially the chemicals sector and furniture have experienced increases in energy consumption due to fast export growth. Rising import shares in final demand have reduced energy consumption in especially the textile sector, whereas rising import shares for intermediate inputs have reduced energy consumption in the textile and machinery sectors. Another result of the decomposition analysis is the sensitivity of results with respect to different levels of aggregation. This is a general problem for all decomposition analyses dealing with energy and using energy intensity. The results for individual sectors can be totally changed by using different aggregation levels.

Energy policy implications and modelling perspectives

Energy policy and environmental regulation has often been examined by analysing initiatives and policies separately or comparing alternative policies. The importance of addressing a set of policy instruments in the same analysis as interaction between policy instruments can be considerable in size is revealed in the paper on the Hybris model and combined initiatives to reduce Danish CO_2 emission. This is also what some of the models referred to in the paper about technological progress is examining. A combination of policy instruments can under certain conditions have a larger impact on energy demand and environmental pressure and less economic costs than if only a single policy instrument were used.

International agreements and domestic energy consumption related to trade can be considerably affected by structural change in trade patterns for a small country as Denmark as reflected in the last paper about Danish trade patterns. Therefore it is important to consider possible changes in future trade patterns, when negotiating and joining international agreements.

For future research the issue of changing consumption patterns can be relevant especially with respect to long-term developments towards an information society with a change in the meaning of work both with respect to place and product. In the light of the Hybris model applied in a number of the included papers there are several model developments that are interesting. Already some models for ADAM sectoral final energy demand have been developed and estimated in the SMP research program and then implemented in ADAM in the EMMA submodel to ADAM. This is relevant for Hybris properties as there now is included a price elasticity for electricity and not only for the sector aggregate energy input. The importance of the determination of electricity price in Hybris has thus been increased. Still the effect of for example a CO_2 tax does not include substitution in favour of natural gas as input in the producing sectors as this is still in EMMA described as an exogenous share of other fuels. To have a more appropriate description of this could have an important impact on the economy wide effect of a tax.

Other aspects of energy markets that Hybris not address are investigated by the ELEPHANT model that focus on the integration of the Danish system in the Nordic electricity production system or the CGE models developed in the Ministry of Business and Trade. Those models are briefly discussed elsewhere in this dissertation. The change of market conditions with the liberalisation of electricity markets makes it relevant to discuss models with strategic behaviour of suppliers and other aspect of market design including the proposed market for green electricity certificates.

The shortcomings and lack of behavioural description of the vintage models for electric appliances and heating devices could be moderated. The possibility of describing the choice between different versions of a given type of appliance with different prices seems one important possibility that will increase the effect of changes in electricity prices and give a better description of the technology diffusion. For heating devices the result that heat prices tend to influence the speed of technology diffusion makes it worth examining this issue further in the residential heating model.

Technology policies seem important as stressed by the two very first papers in this collection but the link between technology policy and energy efficiency is difficult to empirically quantify. Hopefully future attempts in this direction will prove more successful. Technological progress and the extent that R&D drive it require much more research. For energy technology one of the big issues seems to be the degree to which the development is driven by inside R&D or technology spillover from other sectors or public research activities.

9. Appendix: List of variables in the electricity and heat model.

Exogenous variables:

U_u^a Expansion of power capacity (net) — MW_{el}
a= public utilities, non-utility ; u= wind turbines, decentral CHP, industrial cogeneration, miscellaneous
Source: DEF 10 year statistics

T_u^a Annual hours in operation for the total capacity in each category a,u — hours
a= public utilities, non-utility ; u= wind turbines, decentral CHP, industrial cogeneration, miscellaneous
Calculation: E/8760 P
Source: DEF (Danish utilities association): 10 year statistics

v_i^a Share of capacity expansion based on fuel *i* in a given year. — %
a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass
Source: Energy Statistics, Danish Energy Agency, and estimate

${C_{M}}_i^a$ C_m value for the capacity vintage of the categories a, i (C_M only for decentral CHP)
a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass
Source: Energy Statistics Danish Energy Agency, and estimate

η_i^a Fuel efficiency (total) for vintage of capacity expansion of category a, i
a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass
Source: Energy Statistics Danish Energy Agency, and estimate

v_i^F Share of district heating capacity based on fuel i. — %
i= coal, fuel oil, natural gas, biomass
Source: Energy Statistics Danish Energy Agency, and estimate

η_i^F Fuel efficiency for district heating based on fuel i.
i= coal, fuel oil, natural gas, biomass
Source: Energy Statistics, Danish Energy Agency, and estimate

φ Share of final heat demand produced as CHP. — %
Source: DEF 10-year statistics

P_j Power capacity on central plants — MW
j= plant 1..51, + additional planned plants
Source: DEF 10 year statistics, Planning publications from ELSAM / ELKRAFT

Q_j Heat capacity on central CHP plants. — MJ/s
j= plant 1..51, + additional planned plants
Source: DEF 10 year statistics, Planning publications from ELSAM / ELKRAFT

C_M^j C_m value for central CHP plants.
j= plant 1..51, + additional planned plants
Source: DEF 10 year statistics, Planning publications from ELSAM / ELKRAFT

η_j Fuel efficiency (electricity) for central plants.
j= plant 1..51, + additional planned plants
Source: DEF 10 year statistics, Planning publications from ELSAM / ELKRAFT

r_j Availability for plant j.
j= plant 1..51, + additional planned plants
Source: estimate based on publications from ELSAM / ELKRAFT

rP Reserve capacity restriction — %

v Size of new central plants — MW

windP	Capacity value for wind turbines (share accounted for in expansion calculation)	%
C_v^j	C_v heat loss per additional power produced j= plant 1..51, + additional planned plants Source: estimate, Planning publications from ELSAM/ELKRAFT	
gC_v	Annual change of C_v on new vintages of central plants. Source: estimate, Planning publications from ELSAM/ELKRAFT	
$g\eta$	Annual change in fuel efficiency (electricity) on new vintages of central plants Source: estimate,	
gC_M	Annual change in C_m for new vintages of central plants Source: estimate, Planning publications from ELSAM/ELKRAFT	
TI_j	Initial year of production for plant j j= plant 1..51, + additional planned plants Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	year
TS_j	Scrapping of plant j j= plant 1..51, + additional planned plants Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	year
F_j^{ai}	Fuel mix for plant j j= plant 1..51, + additional planned plants; a = max share, min share; i= coal, gas, fuel oil, biomass Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	%
k_j	Plant type for plant j j= plant 1..51, + additional planned plants; 0 = new plants after 1990 (all are variable CHP), 1 = condensing plant, 2 = variable CHP, 3 = back pressure CHP Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	
kF^E	Correction factor for fuel consumption for electricity production (1994 calibration)	
kF^H	Correction factor for fuel consumption for heat produced on central plants (1994 calibration)	
kEm_i	CO_2 content of fuels i= coal, gas, fuel oil, refined oil products average Source: INDUS etc.	kg/GJ
k_i^j	Conversion factor from fuel demand in GJ to fixed price demand (1980 prices) j= fuel demand for electricity production, fuel demand for heat production; i= coal, gas, fuel, biomass Source: calculated from input-output matrices, energy-matrices	kr./GJ
k_m	Conversion factor from fuel supply in GJ to fixed price supply m= coal import, import of refined oil products, domestic consumed part of Danish refined products Source: io-matrices, energy matrices	kr./GJ
kfx_j	Conversion factor from production values in 1980-prices to J j= electricity production, heat production, gas distributed domestically Source: io-matrices, energy matrices	TJ/mill. kr.
F_n^{ai}	Fuel share for new plant n n= new plant 1..75; a = max share, min share; i = coal, gas, fuel oil, biomass Source: Planning publications from ELSAM/ELKRAFT	%
pmel	Import price for electricity Source: DEF 10-year statistics	kr./kWh
pfb_j	Fuel prices net of taxes for fuel j (cif., real fuel prices) j= coal, fuel oil, natural gas, biomass, crude oil Source: Danish Energy Agency, Fuel price assumptions for macroeconomic calculations (1995).	kr. pr. GJ
TCO_i	CO_2 tax i= coal, fuel oil, natural gas, biomass, crude oil	kr. pr. ton CO_2

tf_i	Transport cost for fuel i delivered to plants i= coal, fuel oil, natural gas, biomass, Source: Danish Energy Agency, Fuel price assumptions for macroeconomic calculations (1995).	kr. pr. GJ
piwind	Investment cost for wind turbines Source: estimate	mill. kr. pr. MW
pideckv	Investment cost for decentral CHP Source: estimate, ELSAM/ELKRAFT publications	mill. kr. pr. MW
kdevkv	Share of investment cost that is referred to electricity production for decentral CHP investments Source: estimate	%
pic	Investment costs for central plants Source: estimate, ELSAM/ELKRAFT publications (dependent on technology)	mill. kr. pr. MW
CU_s	Investment cost for other investments than in plants (electricity production) (current prices) s= electricity distribution, environmental facilities, other facilities Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	mill. kr.
$sfiel_m^s$	Distribution of total electricity sector s investments on categories m. s= central capacity (plants), other facilities; m =buildings etc., machinery	%
$sfivarme_m$	Distribution of total heat sector investments on buildings and machinery m= buildings etc., machinery	%
$sfigas_m$	Distribution of total gas sector investments on buildings and machinery m= buildings etc., machinery	%
iel	Debt payments in electricity sector Source: DEF 10-year statistics	mill. kr.
jel	Current profits/losses in electricity sector Source: DEF 10-year statistics	mill. kr.
cavarme	Other current expenditures referred to heat production Source: estimate	mill. kr.
Dvarme	Depreciation on fixed assets in heat production (current prices) Source: estimate	mill. kr.
Avarme	Appropriations in heat production (current prices) Source: estimate	mill. kr.
ivarme	Investments in heat production (current prices) Source:	mill. kr.
igas	Investments in gas sector (current prices) Source:	mill. kr.
$AEEI_j$	Autonomous energy efficiency improvement in industrial energy demand relations (same for all ADAM sectors)) j= ADAM sectors that include dtfve-variable	
pcp	Consumer price index Source: ADAM	1980 = 1
pi	Price on investment goods Source: ADAM	1980 = 1
pxb	Price on domestically produced construction inputs Source: ADAM	1980 = 1
pyf	Deflator for Gross domestic product (at factor prices) Source: ADAM	1980 = 1
lna	Hourly wages in manufacturing Source: ADAM	kr.
bjel	Demand for domestic produced electricity Source: Calculated from ADAM and input-output coefficients	TJ

bjeldk Domestic electricity demand — TJ
Source: Calculated from ADAM and input-output coefficients

bjgas Final demand for natural gas — TJ
Source: Calculated from ADAM and input-output coefficients

bjvarme Demand for district heating — TJ
Source: Calculated from ADAM and input-output coefficients

fxne Production in electricity, heat and natural gas retail distribution (fixed 1980 prices) — mill. kr
Source: Calculated in ADAM

qne1 Employment in electricity, heat and natural gas — 1000 pers.
Source: Calculated from ADAM

fxe Production in energy extracting sector (fixed 1980 prices) — mill. kr.
Source: ADAM

fxng Production in refineries (fixed 1980 prices) (for emission inventory) — mill. kr.
Source: ADAM

fm3k Coal import (fixed 1980 prices) (for emission inventory) — mill. kr.
Source: ADAM

fm3q Import of refined oil products (fixed 1980 prices) (for emission inventory) — mill. kr.
Source: ADAM

fe3 Export of energy products (aggregate) (fixed 1980 prices) (this is now endogenous depending on fuel consumption in electricity and heat production) — mill. kr.
Source: ADAM

ange3 Supply coefficient from refineries to export of energy products — mill. kr.
Source: ADAM

am3qe3 Supply coefficient from import of refined oil products to export of energy products — mill. kr.
Source: ADAM

sds : Corporate income tax revenue. — mill. kr.
Source: ADAM

tsds : Corporate income tax — %
Source: ADAM

fveng Energy input in refineries (fixed 1980 prices) — mill. kr.
Source: ADAM

fcv Private consumption, durable goods (fixed 1980 prices) — mill. kr.
Source: ADAM

fih Investments in new dwellings (fixed 1980 prices) — mill. kr.
Source: ADAM

kh Stock of dwellings (fixed 1980 prices) — mill. kr.
Source: ADAM

U Population — 1000 pers.
Source: ADAM

Endogenous variables:

P_u^a Power capacity in category a, u — MW
a= public utilities, non-utility ; u= wind turbines, decentral CHP, industrial cogeneration, miscellaneous
Source: DEF 10-year statistics

$\bar{P}$ Max load, electricity — MW

$P^{Ø}$ Desired power capacity (minimum capacity) — MW

P^C Central power capacity — MW

P^S Secondary power capacity — MW

RP	Actual reserve power capacity	%
$\overline{E}^C$	Electricity production to be produced on central plants.	GWh
$\overline{H}^C$	Heat production to be produced on central plants.	GWh
Mel	Import of electricity	GWh
E_u^a	Electricity production in category a, u a= public utilities, non-utility ; u= wind turbines, decentral CHP, industrial cogeneration, miscellaneous Source: DEF 10-year statistics	GWh
$E^C{}_j$	Electricity production on central plant j j=plant1..plant 51, new plant 1..new plant 75	kWh
$H^C{}_j$	Heat production on central plant j j=plant1..plant 51, new plant 1..new plant 75	MJ
$T^C{}_j$	Producing time for central plant j j=plant1..plant 51, new plant 1..new plant 75	hours
$mc^C{}_j$	Marginal producer cost for electricity on central plant j j=plant1..plant 51, new plant 1..new plant 75	kr/kWh
H_u^a	Heat production in category a, u a= public utilities, non-utility ; u= decentral CHP, industrial cogeneration Source: DEF 10-year statistics	GJ
$\overline{v}_i^a$	Share of capacity in decentral category a, that is based on fuel i. a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass Source: Energy Statistics Danish Energy Agency, estimate etc.	%
$\overline{C}_{Mi}^{\ a}$	C_m value for decentral capacity in category a, i a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass	
$\overline{\eta}_i^a$	Total fuel efficiency for decentral capacity in category a, i. a= public utilities, non-utility; i= coal, fuel oil, natural gas, biomass	
Q_n	Heat capacity on central plants n= new plant 1..new plant 75 Source: estimate, ELSAM / ELKRAFT planning publications	MJ/s
C_M^n	C_m value on central plants. n= new plants 1..new plants 75 Source: DEF 10 year statistics, Planning publications from ELSAM/ELKRAFT	
C_v^n	C_v (heat loss) on central plants. n= new plants 1..new plants 75 Source: estimate, Planning publications from ELSAM/ELKRAFT	
η_n	Fuel efficiency for electricity production central plants. n= new plants 1..new plants 75 Source: DEF 10-year statistics, Planning publications from ELSAM/ELKRAFT	
F_{ik}^a	Fuel consumption in category a, i, k a= public utilities, non-utility ; i= coal, fuel oil, natural gas, biomass; k= electricity production, heat production	TJ
F^{Cik}_j	Fuel consumption on central plant j for electricity and heat production k= electricity-, heat production; i= coal, fuel oil, natural gas, biomass; j=plant1..plant51, new plant 1..new plant 75	TJ

F_i^{Ck}	Fuel consumption on central plants in total for electricity and heat production k= electricity-, heat production; i= coal, fuel oil, natural gas, biomass	TJ
F^{KV}_i	Fuel consumption for heat produced on central plants i= coal, fuel oil, natural gas, biomass	TJ
F^{V}_i	Fuel consumption for heat produced on district heating plants i= coal, fuel oil, natural gas, biomass	TJ
F_i^H	Total fuel consumption for heat production i= coal, fuel oil, natural gas, biomass	TJ
F_i^E	Total fuel consumption for electricity production i= coal, fuel oil, natural gas, biomass	TJ
CF^{KV}_i	Fuel costs for heat produced as CHP i= coal, fuel oil, natural gas, biomass	mill. kr.
CF^{V}_i	Fuel costs for heat produced on district heating plants i= coal, fuel oil, natural gas, biomass	mill. kr.
CF_i^H	Total fuel costs for heat production i= coal, fuel oil, natural gas, biomass	mill. kr.
CF_i^E	Total fuel costs for electricity production i= coal, fuel oil, natural gas, biomass	mill. kr.
Emnel	Emission of CO_2 from electricity production Source: DEF 10-year statistics	ton
Emnev	Emission of CO_2 from heat production Source: DEF 10-year statistics	ton
Emne	Emission of CO_2 from electricity and heat production Source: DEF 10-year statistics	ton
Em_i	Total emission of CO_2 in DK attributable to fuel (aggregate) j j= coal, import of refined oil products, natural gas, domestically refined products Source: Danish Energy Agency, calculations	ton
Emprovne	CO_2 tax revenue from electricity and heat production Source: Calculated	mill. kr.
Emprov	Total revenue of a CO_2 tax Source: Calculated	mill. kr.
D_l	Depreciation according to legislation in electricity production (current prices) l= central plants, other facilities	mill. kr.
A_l	Appropriations in electricity according to legislation (current prices) l= central plants, other facilities	mill. kr.
wel	Wages in electricity production (current prices) Source: DEF 10-year statistics	mill. kr.
mel	Other input costs in electricity production (current prices) Source: DEF 10-year statistics	mill. kr.
CU_s	Construction costs for electricity producing facilities s= central plants, wind turbines, decentral CHP	mill. kr.
Cel	Total costs of electricity production (current prices) Source: DEF 10-year statistics	mill. kr.
Cvarme	Total costs of heat production (current prices) Source:	mill. kr.
Fgas	Fuel cost in natural gas distribution	mill. kr.

Source:

Dgas Deprecations in natural gas distribution (current prices) mill. kr.
Source: estimate

Agas Appropriations in natural gas distribution (current prices) mill. kr.
Source: estimate

Cgas Total costs in natural gas distribution (current prices) mill. kr.
Source:

iel_m^s Investments in electricity production (current prices) mill. kr.
s= central plants, other facilities ; m= buildings etc., machinery

$ivarme_m$ Investments in heat production (current prices) mill. kr.
m= buildings etc., machinery

$igas_m$ Investments in natural gas distribution (current prices) mill. kr.
m= buildings etc., machinery

COf_i CO_2 tax on fuel i kr. pr. GJ
i= coal, fuel oil, natural gas, biomass, crude oil

pf_i Price of fuels (real cif. prices) *pfb* inflated by *pfy* and including tax kr. pr. GJ
i= coal, fuel oil, natural gas, biomass, crude oil

pfv_i Price of fuels delivered at plant incl. tax and transport cost kr. pr. GJ
i= coal, fuel oil, natural gas, biomass, crude oil

ph Shadow price on central heat production, (ensures that total demand is met) kr./kWh

pe Price on electricity production from individual plant (variable cost) kr./kWh
pe max is variable cost from marginal plant (shadow price)

pxnel Output price for electricity 1980=1
Source: Input-output matrices

pxneg Output price for natural gas distribution 1980=1
Source: Input-output matrices

pxnev Output price for heat production 1980=1
Source: Input-output matrices

elpris Electricity price (following legislation) kr. pr. kWh
Source: DEF 10-year statistics

aane Coefficient for agricultural inputs to electricity and heat production, (natural gas distribution)
Source: ADAM

am3kne Coefficient for coal import for input to electricity and heat production, (natural gas distribution)
Source: ADAM

am3qne Coefficient for import of refined oil products for input to electricity and heat production, (natural gas distribution)
Source: ADAM

angne Coefficient for domestically refined oil products for input to electricity and heat production, (natural gas distribution)
Source: ADAM

aene Coefficient for energy extraction inputs to electricity and heat production, (natural gas distribution)
Source: ADAM

anene Coefficient for own deliverance to input in electricity and heat production, (natural gas distribution)
Source: ADAM

fimne Investments in machinery in electricity and heat production , (natural gas distribution) (fixed prices) mill. kr.
Source: ADAM

fineb ? Investments in buildings etc. in electricity and heat production, (natural gas distribution) (fixed prices) mill. kr.
Source: ADAM

varmepris Average price for heat kr. pr. GJ
Source: Danish Energy Agency, estimate

gaspris Price of natural gas (retail) kr. pr. GJ
Source: Danish Energy Agency, estimate

pxne Output price (weighted) for electricity and heat production, (natural gas distribution) 1980=1
Source: ADAM

jrpxe Adjustment parameter in ADAM price relation for electricity and heat production, (natural gas distribution)
Source: ADAM

pm3r Crude oil price 1980=1
Source: ADAM

kpm3q Adjustment coefficient for import price for refined oil products
Source: ADAM

kpm3k Adjustment coefficient for import price for coal
Source: ADAM

jdam3kne Adjustment parameter in coal import input coefficient in electricity and heat production, (natural gas distribution)
Source: ADAM

jdam3qne Adjustment parameter in imports of refined oil products as input to electricity and heat production, (natural gas distribution)
Source: ADAM

jdangne Adjustment parameter in domestic refineries deliverance as input to electricity and heat production, (natural gas distribution)
Source: ADAM

jdanene Adjustment parameter in inputs of own production for electricity and heat production, (natural gas distribution)
Source: ADAM

bene Share of extraction sector production that is used as input to electricity and heat production, (natural gas distribution)
Source: ADAM

fe3 Energy export (fixed prices) mill. kr.
Source: ADAM

zfkmne Exogenous machine capital in ADAM *ne* sector (electricity and heat production) mill. kr.
Source: ADAM

zfvene Exogenisation variable in ADAM for electricity and heat production (natural gas distribution) (fixed prices)mill. kr.
Source: ADAM

anelne Danish electricity input in electricity and heat production (natural gas distribution) (coefficient)
Source: input-output matrices

anegne Danish deliverance from natural gas distribution (retail) to electricity and heat production (natural gas distribution) (coefficient)
Source: input-output matrices

jsdsr Adjustment parameter in corporate tax revenue
Source: ADAM

jtsdsu Adjustment parameter in expected corporate tax rate
Source: ADAM

tm3r Import tariff on crude oil
Source: ADAM

tm3k Import tariff on coal
Source: ADAM

tm3q Import tariff on refined oil products
Source: ADAM

tvene Tax on energy input in electricity and heat production (natural gas distribution)
Source: ADAM

tveng	Tax on energy input in refineries Source: ADAM	
kpe3	Adjustment parameter for export price of energy Source: ADAM	
anee3	Export deliverance from electricity and heat production (natural gas distribution) (constant electricity export) Source: ADAM	
fane	Biomass deliverance from agriculture to input in electricity and heat production (natural gas distribution) (fixed prices) Source: ADAM	mill. kr.
fcex	Private consumption of electricity and heat (exogenous to ADAM version) (fixed prices) Source: ADAM	mill. kr.
anece	Coefficient for deliverance from electricity and heat production (natural gas distribution) to fce Source: ADAM	
anelce	Coefficient for electricity deliverance to *fce* Source: input-output matrices	
anegce	Coefficient for natural gas deliverance to *fce* Source: input-output matrices	
anevce	Coefficient for heat deliverance to *fce* Source: input-output matrices	

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