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Energy technologies and energy efficiency in economic modelling

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Abstract

This paper discusses different approaches to incorporating energy technologies and technological development in energy-economic models. Technological development is a very important issue in long-term energy demand projections and in environmental analyses. Different assumptions on technological development are one of the main causes for the very diverging results which have been obtained using bottom-up and top-down models for analysing the costs of greenhouse gas mitigation. One of the objectives for studies comparing model results have been to create comparable model assumptions regarding technological development.

This paper examines the effect on aggregate energy efficiency of using technological models to describe a number of specific technologies and of incorporating these models in an economic model. Different effects from the technology representation are illustrated. Vintage effects through the slow replacement of production capacity is important for the rate of efficiency improvement. Short-term changes in Danish power production are very large due to changing situations in the Nordic hydropower system. The effect of the changing utilisation rates for power capacity in Denmark illustrates the dependence of average efficiencies and productivity on capacity utilisation rates. In the long run regulation induced by environmental policies are also very important for the improvement of aggregate energy efficiency in the energy supply sector. A Danish policy to increase the share of renewable energy and especially wind power will increase the rate of efficiency improvement. A technologically based model in this case indirectly makes the energy efficiency endogenous in the aggregate energy-economy model.

1. Introduction

Technological development is an important issue in both economic and energy-related analyses which have a horizon of more than just a few years. Technological change can be seen from a very detailed perspective of a specific innovation of some equipment. On the other hand this detailed innovation or improvement in the way some equipment is used could be viewed from an aggregated energy-economic description of the development of energy efficiency.

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 another is explaining why the technological change is taking place or being implemented. The focus in this paper is on the aggregation of specific technologies and the effects on average energy efficiency, which can be identified by such an approach.

In energy-economy models the descriptions of energy efficiency developments are represented by giving varying degrees of priority to explaining innovations. The representations range from exogenous and constant rates of efficiency improvement AEEI (autonomous energy efficiency improvement) to endogenised technological development.

A lot of arguments can be found against a constant AEEI, and especially if the horizon is not very long (less than 50 years) the short- or medium-term developments in energy efficiency will depend on a variety of factors as capacity utilisation, vintage effects from new investments, public policy, specific innovation of new technologies 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. An example of using a bottom-up model for the description of the development in aggregate energy efficiency will be presented in this paper.

In the long run the importance of new inventions and innovations will be the dominant factor in explaining efficiency developments. Bottom-up or technical models do not focus on explaining innovations, but these models do describe technologies in detail that are not yet fully developed for commercialisation. By the dependence on fuel prices, regulation and investment activity, the aggregate energy efficiency is described with a kind of endogenous implementation of technologies but not endogenous technological development.

2. Autonomous energy efficiency improvement or endogenous technological change

Energy-economy models have very different descriptions of technological change. At the same time technological change is an important element in stating the properties of the model 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 progress.

Some of the different approaches to modelling energy technologies and energy efficiency improvement can be categorised by:

- AEEI - exogenous and constant energy efficiency improvement
- AEEI- distinguishing between price-induced and time-induced improvements
- Optimising long-term technology between some aggregate technologies with different efficiencies (energy supply sector)
- Vintage models of capital with energy efficiencies related to vintage (general economy-wide representation)
- 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 range from an annual efficiency improvement of ½% to 1½%. Apart from this exogenous component of energy demand, the prices of production factors capital, labour and energy shift the factor input composition. Hereby the energy intensity of production also changes. The AEEI is time dependent but instead of remaining constant the autonomous efficiency change could follow estimated nonlinear time trends.

A possible extension of this approach is to link the efficiency improvement to energy prices, but it will be hard to establish an empirical distinguishing between price-induced shifts in factor inputs and price-induced improvement of efficiency.

An AEEI representation of efficiency improvement in specifications of energy demand for heating in households could, for example, be

$$E_j = e(p_i, p_j, aeei, C) \tag{1}$$

p_j Price of different heating technology: 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 AEEI representation in households thus accounts for efficiency improvements induced by improved insulation of existing houses, efficiency improvements in specific heating technologies, standards for new dwellings and the introduction of new heating technologies not represented in the modelling specification.

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 estimates of future rates of introduction of new technologies. The technical view includes limits on the increase in energy efficiency. For existing technologies these limits seem plausible as fuel efficiencies would hardly increase above 100%. 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 economic view does not have any assumption of limits for energy efficiency or decreasing rates of energy efficiency improvement. Only when production of a single output or very specialised sectors are examined will production technologies be modelled in detail, and thus the properties from technological models will arise.

Energy-economy models with optimisation of the choice between specific energy technologies dependent on total discounted profits and based on rational expectations include 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.

Vintage effects as different energy efficiency for different vintages of capital could be important for year to year changes in energy efficiency. Vintage models of capital have been applied to fields of energy relevance. Both technical vintage models of durable consumer goods (appliances) and vintage models of energy supply exist. More macroeconomic based model approaches of capital vintages for producing sectors in general and their energy efficiency have also been proposed. Energy efficiency is seen as embodied in the new capital vintages. Berndt et. al. (1993) examine the empirical evidence of embodied and un-embodied 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 seems to be quite small. Their study examined the overall 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, as investments will probably be higher at periods of high capacity utilisation. These effects will be examined using a model of the energy supply sector. 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.

Long-term energy demand and environmental issues related to this will depend very much on the possible invention of new technologies. These could be new energy technologies, but they could also be production technologies, inventions in transportation etc. Thus energy efficiency will depend on technological developments that have nothing to do with an aim of improving energy efficiency. This dependence means that no energy or environmental policy option exists for influencing this part of energy efficiency development. Innovation with specific relevance for energy technologies is a more relevant area to model if the aim is analysing possible policy instruments that influence energy efficiency. Carraro and Galeotti (1997) describe an endogenous modelling of innovation in energy technologies. The innovation is related to R&D which again is endogenously determined by prices, output and policy variables as environmental taxes and R&D subsidies. The endogenous technological progress has been analysed in many theoretical models but the WARM model has an advantage in that the technology representation is empirically founded.

3. Which possible explanations for changes in aggregate energy efficiency can be identified and quantified by using a bottom-up description in energy-economy models?

This section excludes the question of explaining the innovation of new energy technologies itself. Instead the focus is on improving an exogenous description of energy efficiency developments. There are several interesting issues and questions:

- Is the embodiment hypothesis more relevant for capital intensive and long-lived capital sectors as the energy supply sector?
- 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 effect 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 could include the energy supply sector and household consumption of energy for heating purposes.

4. An example of technological development in a model of the energy supply sector

The aggregated energy efficiency from an energy-economy model illustrates some of the interdependencies between technological development, investments, capacity utilisation and public policy. These dependencies are illustrated in examples using a

Danish model and the Danish energy system as a case. A case of the energy supply sector emphasises the partly endogenised average energy efficiency in power production - fuel price and policy influences the average efficiency development.

The model named Hybris 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 purpose of that project was to identify theoretical and methodological problems for 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 the energy supply sector of the macroeconomic model as well as 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 Hybris model is described in detail in Jacobsen et. al. (1996).

The energy supply module of Hybris is very detailed. Power and heat production are described including all the major combined heat and power plants in Denmark. Long-term technology choices are seen mainly as restricted by public regulation. Short-term decisions are unregulated. The demanded heat and power are being produced at the main plants, where production is allocated between the plants to minimise the total costs of producing the joint products heat and power.

Four different elements that contributes to changes in fuel efficiency in the energy supply 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 longer-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 power production follows the domestic energy demand development.

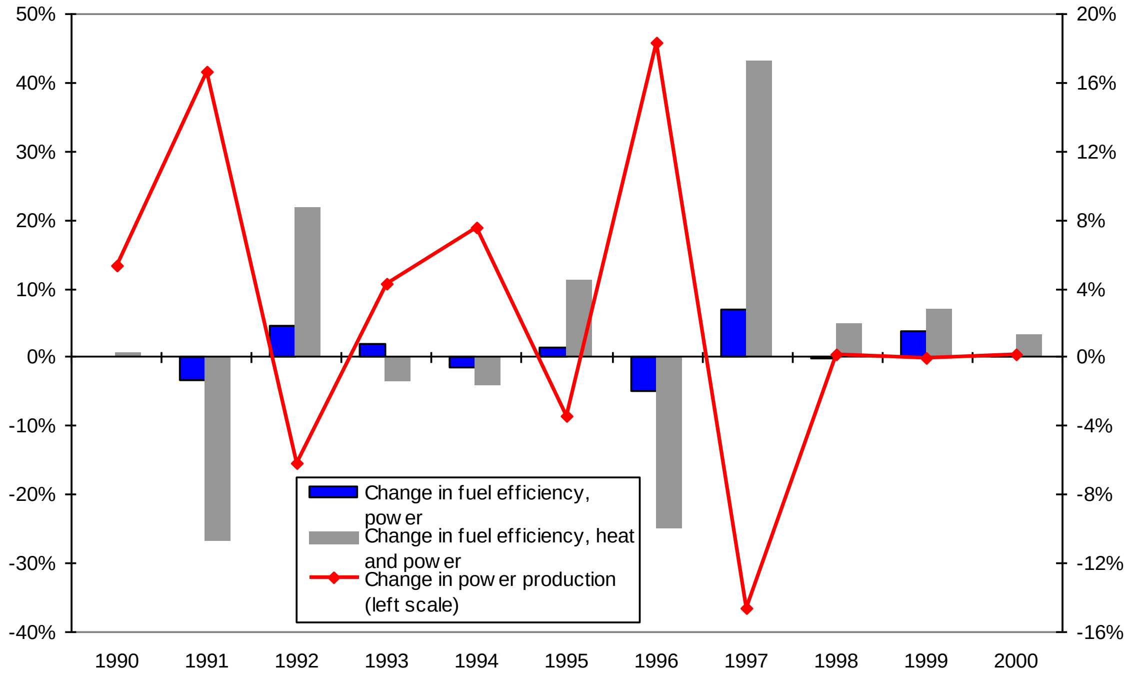

Figure 1 Fuel efficiency changes and changes in power production

Danish power production has fluctuated markedly 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.

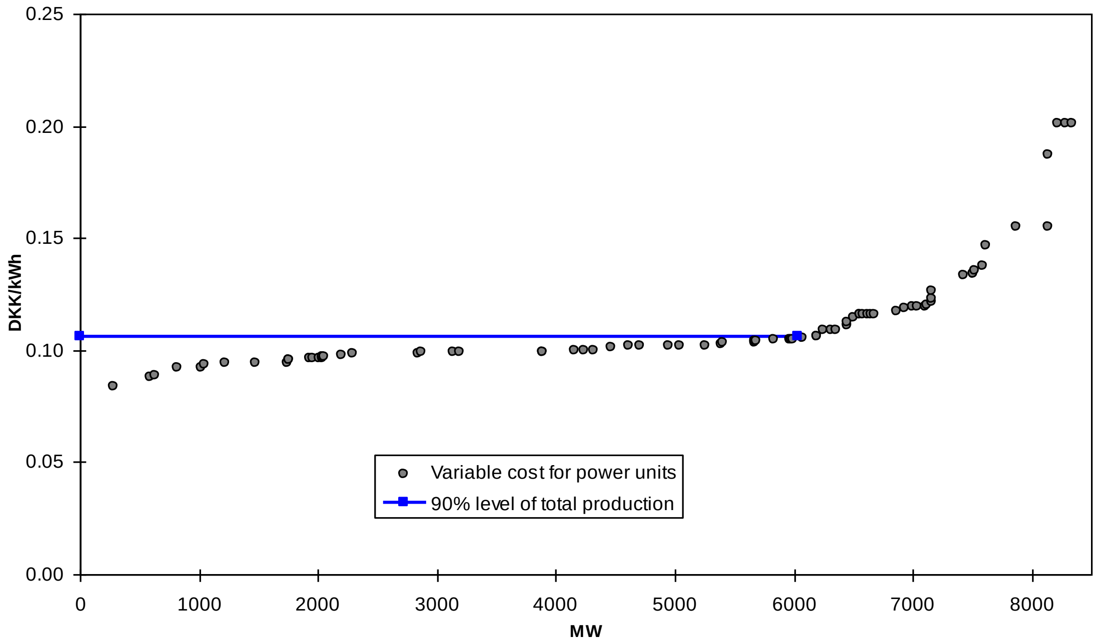

Figure 2 Marginal production costs for Danish power-producing units 1996

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 shifting 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. 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 a straight line.

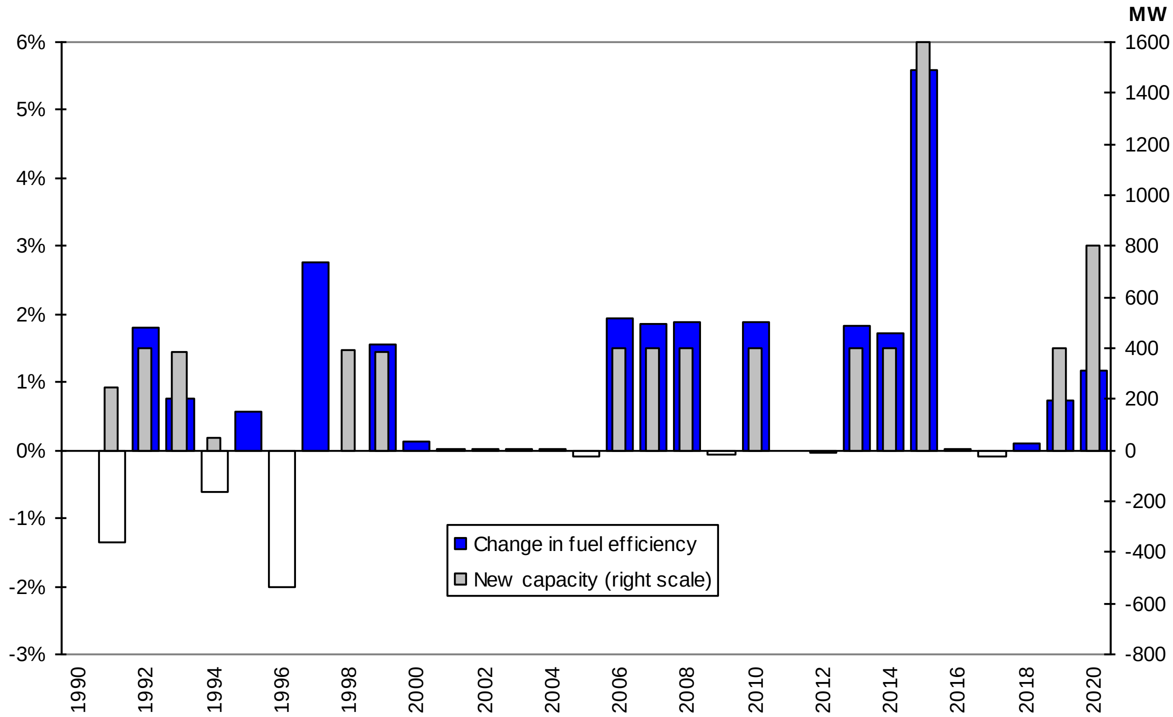

Figure 3 Fuel efficiency changes relates to introduction of new capacity

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 efficiency improves around 2%. New plants improve overall efficiency because their fuel efficiency is better than the older plants and because they capture a relatively large share of the total production. The new plants are running nearly all year and produce around 5% of total production by major 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 is natural gas based 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 is a result of decreasing production in 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.

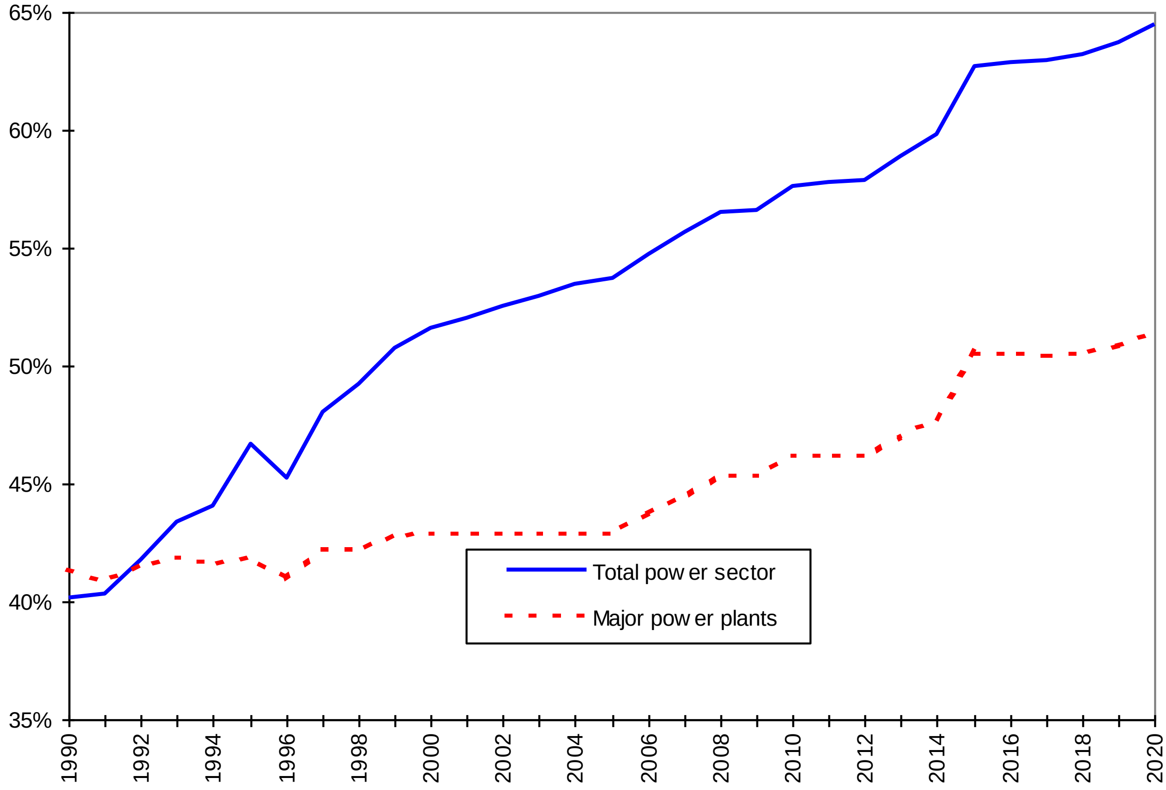

Figure 4 Fuel efficiency in power production: projection based on energy policy

The importance of public policy is evident from the different slopes of the two curves in Figure 4. The expansion of wind energy increases the average ***fuel*** efficiency in power production. This is accomplished by increasing the capital equipment in power 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 average energy efficiency in power production. This effect would be difficult to quantify in another model that did not have the detail that is in this model of the energy supply sector. Thus, for all energy and environmental analysis including policy instruments as, for example, priority given to renewable energy, a detailed energy technology description will be important.

Efficiency indicators are relatively unproblematic at the disaggregated level of fuel (TJ) used for power production (kWh). Compared to this the aggregation of fuels and comparison with GDP developments is a much less accurate measure of energy efficiency.

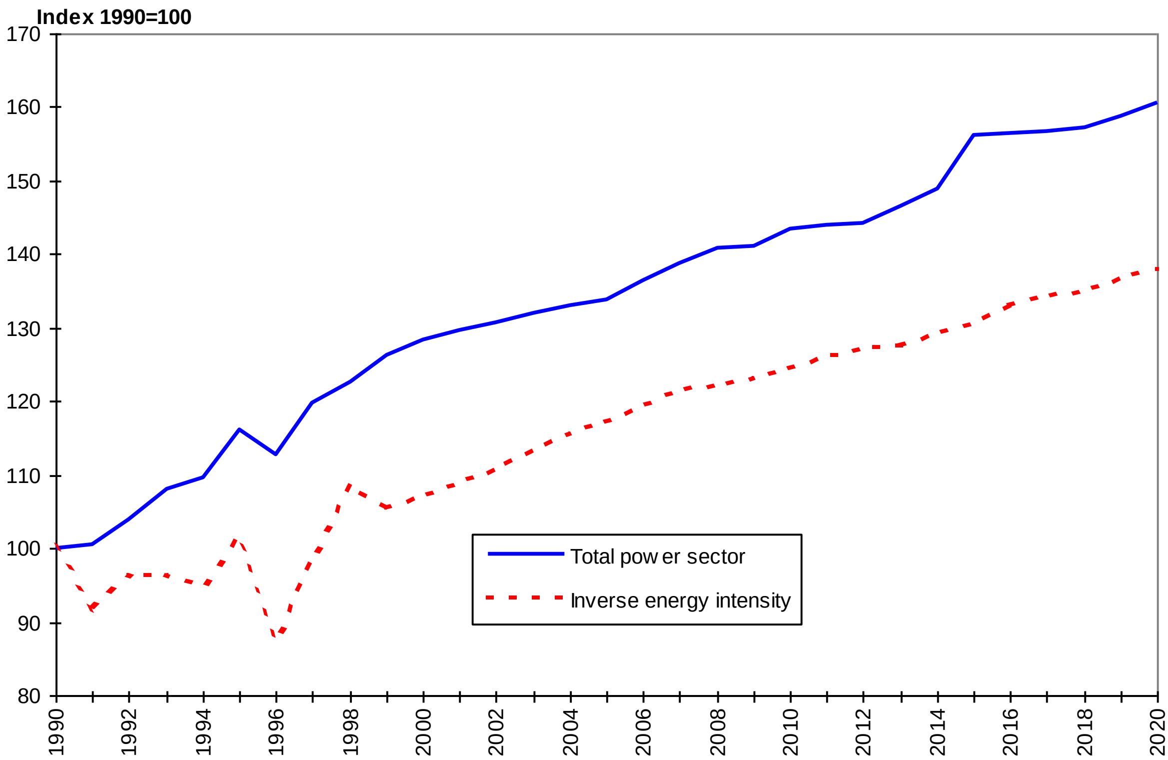

Figure 5 Energy efficiency in the power sector and energy intensity of the Danish economy

In Figure 5 the energy intensity in economy fluctuates more than the fuel efficiency in the power sector. The changes in power production are the reason that the energy intensity of the economy fluctuates greatly. 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 lead to even more detailed decomposition analyses of what is the basic development of efficiency.

Figure 5 shows that in the long run efficiency increases more gradually for the economy-wide measure than for fuel efficiency in power. The importance of the power sector for the economy-wide energy efficiency is strongest in the first years, but in the long run it is both the efficiency increases in the power sector and the relative increase in electricity in final demand that boosts overall energy efficiency.

5. Energy efficiency changes in household heating demand

This section describes a case of the Hybris model with respect to 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 change in this average heating efficiency is compared to the average consumer price for heating in households. Both series are three-year moving averages.

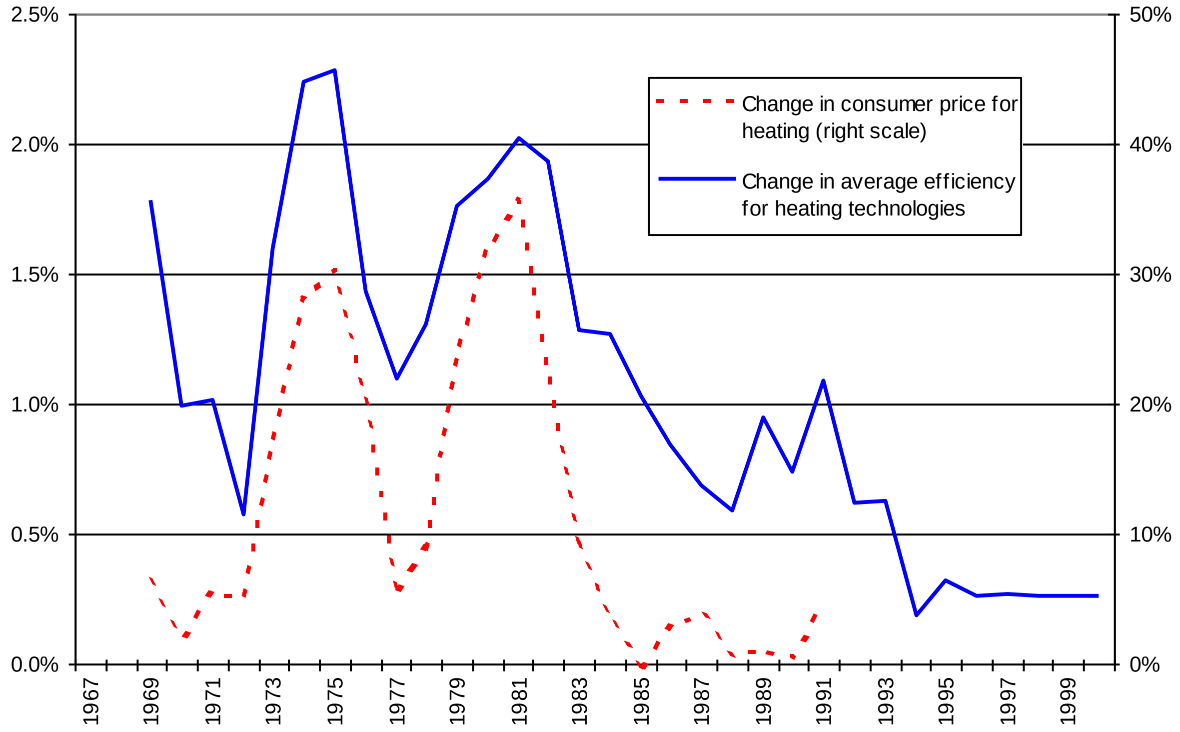

Figure 6 Change in average heating efficiency depends on prices

The 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.

6. Conclusions

Technology development is a critical parameter for a long-term analysis of energy and environmental issues. Macroeconomic-oriented energy-economy models have a very aggregated and generalised description of the change in energy technologies. It is possible to endogenise the technology at the aggregated level, but it is very difficult to establish empirical results to verify the endogenisation. Another approach is to give a priority to the description of existing specific technologies and the immediate following technologies. This leaves the question of fundamental innovation out, which is a highly relevant question when attempting macroeconomic modelling to endogenise technical progress.

Technical descriptions of a long range of specific technologies could be used for analysing possible dependencies of the overall efficiency development. With technical bottom-up based models the vintage effects of capital vintages on average efficiency can be quantified. It is possible to include effects related to the division of production between different vintages of capital. New capital will be used to a relatively greater extent than older capital, the use of which will increase as average capital utilisation rates increase. Energy efficiency in general will not have a high cost share of total production costs. That means that it is not always the most energy-efficient capital which constitutes investments. Thus, energy efficiency cannot be treated in the same way as general production efficiency.

Energy and environmental policies have an important impact on energy 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 technologically based models, which could make a consistent quantification of policies including those effects which work through prices and demand.

The examples from the energy supply sector show that capacity utilisation rates have some influence on the rate of fuel efficiency improvements in the short run. Vintage effects are also important for explaining aggregate changes in energy efficiency for a sector such as energy supply. The Danish energy policy of increasing the use of renewable energy sources, especially wind energy, of course increases the total fuel efficiency for power production. With a technical description of the sector it is possible to quantify this effect of the policy in a consistent way.

Acknowledgements

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