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Modelling energy technology diffusion. Energy policy implications

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Abstract

Technological development is a very important issue in long-term energy demand projections and in environmental analyses. Different assumptions on technological development and diffusion of new technologies can have substantial impacts on long-term energy demand projections. This paper examines policies that are designed to increase energy efficiency in a context of technological vintage models that describe technology diffusion. Especially the diffusion of technology as a consequence of introducing standards is examined.

Diffusion of energy technologies can be seen from a very detailed perspective of a specific technology or equipment. On the other hand this detailed description of improvement could be aggregated to an energy-economic description of the development of energy efficiency.

A number of Danish energy supply and energy demand models are used to illustrate the consequences of the vintage modelling approach. For example, the diffusion of electric appliances is linked to economic activity and saturation levels for each appliance.

An important issue for comparing energy demand projections from models based on different approaches to technological progress is the difference of policy effects among the approaches. In some models long-term energy demand can only be affected by exogenous price changes or taxes. In other models a range of policy instruments can influence the efficiency developments. In the vintage model for electric appliances used in here taxes also have an impact on the intensity of use for some of the appliances, but the effect is limited. The vintage model due to its detail includes a number of policy instruments, which is examined in this paper.

INTRODUCTION

Energy policy both directly and indirectly affects technological progress. The policy effect works through many channels and the effect is very difficult to identify and quantify. A number of analytical studies have addressed incentives and policies to promote technological progress. Milliman and Prince (1989) compare incentives for innovation and diffusion under five different regulating regimes. 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. 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.

Model based policy analyses has only recently been devoted to analysing policies that affect technological progress. R&D related policies have been examined as well as policies that accelerate diffusion.

Technological progress can be divided into innovation and diffusion of technologies. Innovation determines the very long-term development of technological progress, whereas diffusion of existing technologies is important in the short to medium term perspective. Diffusion is embedded in many kinds of energy models, of which the vintage model is an important example. Vintage models do describe diffusion of technologies, but in most cases an explanation is not given.

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. The imperfections result in too slow technology diffusion and removing the imperfections and other barriers can speed up the diffusion process.

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.

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 Nixon, 1997) compares a model with endogenous technical progress (diffusion) to a similar model, which however, include exogenous technological progress.

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.

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. Vintage models can be applied to analyse both aspects of possible policies for increasing the speed of diffusion.

The first kind of diffusion can for example be analysed in relation to vintages of power producing plants. It is the **production** of the new vintages that is important and hereby an increased diffusion measured by share of power produced by new vintages will improve energy efficiency (fuel efficiency in conversion).

Diffusion of a new product is in focus if it is the residential energy demand that is considered. Vintage models of electric appliances can be applied in this case.

Vintage effects play an important role in determining the rate of technological improvement in energy efficiency. Some relevant examples are the energy supply sector and household consumption of energy for heating and electric appliances. In the next section vintage models for these sectors will be used for illustrating some of the important issues identified above.

VINTAGE MODELS AND POLICY INSTRUMENTS TO INCREASE THE SPEED OF DIFFUSION

This section focuses on the relations that affect technological progress and the policy options for increasing the speed of technology diffusion. When recognised as one of the major factors affecting long-term energy demand it is obvious that the issue of designing policies that accelerate technological progress attract much attention. Vintage models are a possible context in which to analyse technology policies. These kinds of models are suited to analyse diffusion of existing technologies but do not address the issue of innovation policies. There are several interesting policy issues and questions that can be analysed in vintage models:

- To which degree is technological progress embodied in a vintage for a range of final energy demand categories? Is there any difference between electric appliances and residential heating devices?
- How can the average efficiency of a vintage be affected? Are standards a relevant policy instrument in this case?
- What about the rate of capacity utilisation? Is it possible or even attractive to reduce capacity utilisation by increasing investment and hereby increasing average efficiencies?
- Do environmental policies affect the development of energy technologies?
- Do energy prices and taxes affect the speed of implementation?

Vintage models will be most relevant to use if technological progress to a large extent is embodied in new vintages of capital equipment of durable consumer goods. With respect to electric appliances the technological progress will mainly be embodied in the new vintage of an appliance. When first purchased the appliance will never become more efficient. Even though the efficiency cannot be changed the electricity can to some extent be influenced by changes in intensity of use. For appliances that households have more than one unit the least efficient one will probably be used less. This can be the case for refrigerators or freezers, but probably not many other electric appliances. Contrary to this, heating devices can be improved by improving insulation and by increasing maintenance.

There are many possible policy instruments to affect technology diffusion:

- Standards
- Taxes and duties
- Subsidies
- Appropriations - legislation
- Financing
- Risk elimination

Standards can be analysed dependent on the characteristics of vintage model. Standards specifying the least efficient appliance allowed in the market for a given vintage is the most obvious version. Setting up standards for future vintages is another possible strategy that can have additional incentive effects. Standards will be used most in cases, where the technology in focus is a rather homogenous product, for example, electric appliances in households or fuel efficiency in private cars.

Energy taxes and duties can be analysed in some vintage models that include optimising behaviour for the choice between different production technologies for each vintage or different brands of a given electric appliance. Energy taxes will decrease the average lifetime of an appliance if the consumer consider economic lifetime and not only physical lifetime of the appliance. Taxes will also have an impact on the relative use of different parts of the capital stock. Increased energy taxes will increase the capacity utilisation for new vintage relative to old vintages. Vintage models that keep track of energy efficiencies as well as other inputs for a given vintage can be used to address such a situation. Increased taxes will reduce the average capacity utilisation rate. Indirect energy taxation as taxes on the least efficient capital equipment is another possibility.

Different types of subsidies can be analysed in vintage models. The first option is to subsidise an energy efficient version of an appliance or production equipment, which is too expensive to be competitive in the market. This kind of a subsidy will reduce the economic lifetime for a vintage and hereby increase the average efficiency. Another possibility is a subsidy to scrap the least efficient vintages. The last possibility is to subsidise the use of specific kinds of energy or fuels. Subsidising the capital equipment itself could be distinguished from the possibility of subsidising improvements in the energy efficiency of the capital stock, which is not so obvious to analyse in a vintage model. Embodied technical change is related to vintages of capital as opposed to un-embodied technical progress.

Improved possibilities for appropriations in general will decrease the average age of production capacity. Targeted appropriation possibilities for environmental friendly energy equipment is another possibility.

Access to financing can be restricted for financing of new and unproven energy technologies. The same can be the case for old polluting industries that are exposed to severe competition and hereby maintain an old production capacity. Setting up long-term financing facilities for energy efficient equipment will thus be an alternative policy that can increase the speed of technology diffusion.

This policy is related to the risk associated with using new energy technologies and the risk associated with some of the long-term investment decisions that characterise energy equipment. Reduced risk will increase investments and energy technology diffusion.

For the energy supply sector and to some extent other energy intense industries the energy consumption will be 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 will in the case of the energy supply sector be the main explanation of 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. 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.

In another type of vintage model concerned with residential electricity demand 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.

STANDARDS AND INVESTMENT SUBSIDIES

In this section two vintage models are used to analyse policies of introducing standards and giving investments subsidies. Both policies are introduced to increase the diffusion of high-efficiency technologies. The vintage models are described in Jacobsen et. al (1996) and in Jacobsen (1998).
The policy involving standards is analysed in a vintage model of electric appliances and investment subsidies is analysed in a vintage model for the power producing sector in Denmark. The policy effect on diffusion and efficiency improvement cannot be compared as they are evaluated using quite different models. The two policies examined are:

a) Demand side regulation in the form of standards for the maximum electricity consumption of household appliances for sale.
b) Subsidising new efficient power plants to replace existing capacity

Residential electricity demand is characterised by a number of electric appliances that constitutes a major part of residential electricity consumption. Each category of appliances consists of homogenous equipment with respect to the service delivered but with large variations in electricity use.
The efficiency effect of standards will depend very much on the variation of efficiency for existing versions of a given appliance. For the appliances in the model applied here the efficiency of, for example a refrigerator varies a great deal. The most efficient version in Denmark (1992) uses around 150 kWh annually whereas the least efficient version uses around 350kWh a year. With such a variation the possibility for standards to improve average efficiency is very large.

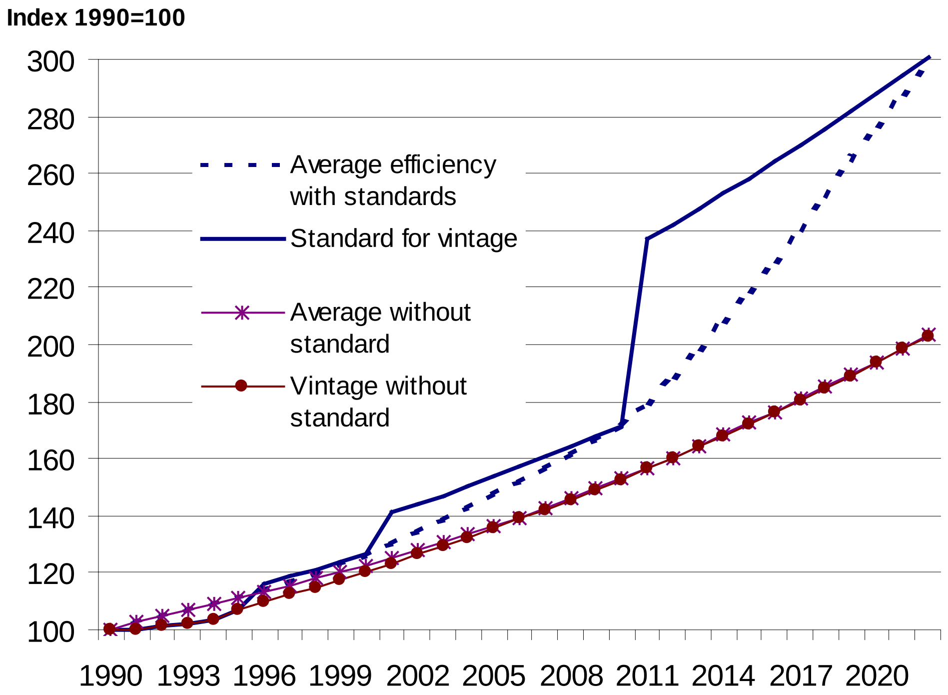

Figure 1 Efficiency developments for washing machine with and without standards.

The standards are introduced for six of fourteen electric appliances. The washing machine example in the graph shows the gradual tightening of the standard. In 1996 the first standard is introduced, which is then tightened in 2000 and in 2010. In 2010 the only allowed version is the one corresponding to the most efficient one available in 1990. Average efficiency for the stock is always lower than the vintage efficiency but the gradual increase in average efficiency as the technology of the tightened standard diffuse is evident in the graph. The standard results in a long-term increase of average efficiency close to 50% relative to the reference. When the second tightening is diffused through the stock around 2010 the average washing machine efficiency is increased by 12% with the least efficient (¾ of the versions) excluded from the market.

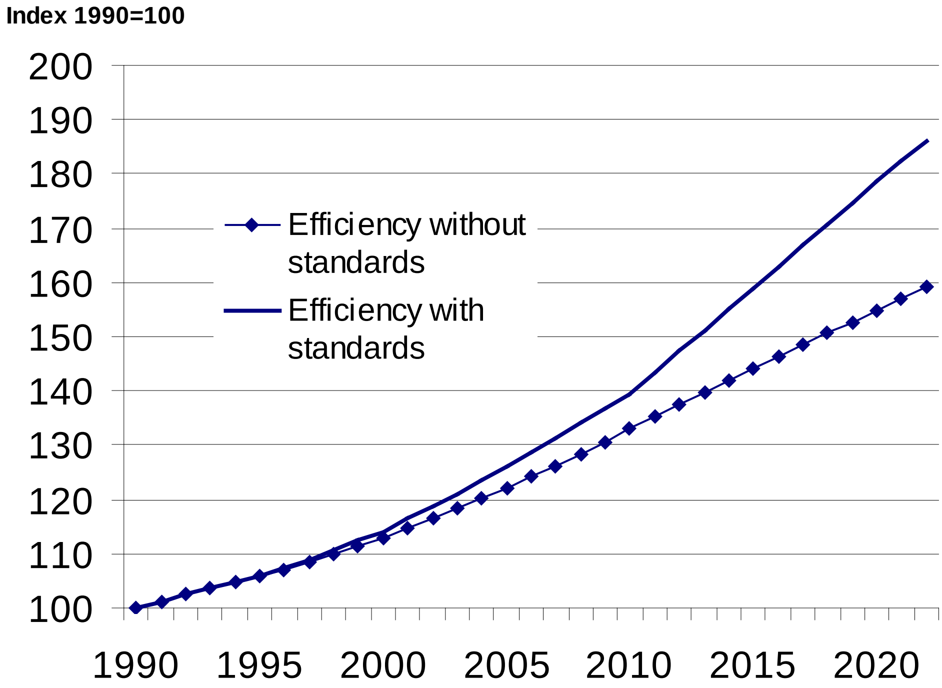

Figure 2 Weighted efficiency for 14 electric appliances

The efficiency increase for the 14 categories of electric appliances are weighted with the electricity consumption of the respective category. The efficiency effect is not as great as for the washing machine above as it is only six of the 14 categories that are covered by a standard. Another explanation is the variation in assumptions about exogenous improvement in efficiency. For the washing machine 2.4% annual efficiency increase is assumed compared to no exogenous efficiency improvement for 7 of the appliance categories. The improvement in efficiency as a result of the policy is increasing in time. This is caused by the gradual diffusion of the efficient versions of the appliances in combination with the gradual tightening of the standard. The introduction of standards for six categories of appliances result in an average increase of 15% in electricity efficiency for 14 electric appliances that constitute the major part of residential electricity consumption. This increase requires very tight standards and a period of diffusion for the new standard. The largest efficiency increase is only achieved by moving to the standard corresponding to the most efficient version in 1990.

The costs of implementing the standards are assumed to be paid by consumers that have to by more expensive versions of their appliances. There is no cost calculation in this model, which means that the implicit assumption is that the reduced electricity consumption will balance the increased price for the appliances. Also this model don't address the issue of cost posed on consumers by limiting the variation in the number of different versions of a given appliance available in the market.

Table 1 Policy effect on average efficiency relative to reference efficiency

Analysed initiative	10 years	15 years	25 years
Standards			
Efficiency effect	3.3%	4.9%	15.3%
Investment subsidy			
Efficiency effect	8.3%	5.1%	3.4%
Investment mill. DKK	15692	-	-
Fuel cost reduction mill. DKK	734	1997	4168

The next example of a policy to increase diffusion considers the case of power production and subsidies to new capacity that replaces production by older production capacity. The investment subsidy is simply the investment cost reduced by the saved fuel costs. Investment subsidies are given in the period 2000-2005. The reduction in total fuel cost covers accumulated figures for the period 2000-2020. It is assumed that the subsidies are given to the producers that are reducing their production on less efficient plants. No value is assigned to the potential for exports, which will be considerably increased as the Danish excess capacity is kept at a high level. The real subsidy necessary to provide incentives for investment will probably be less than stated her.

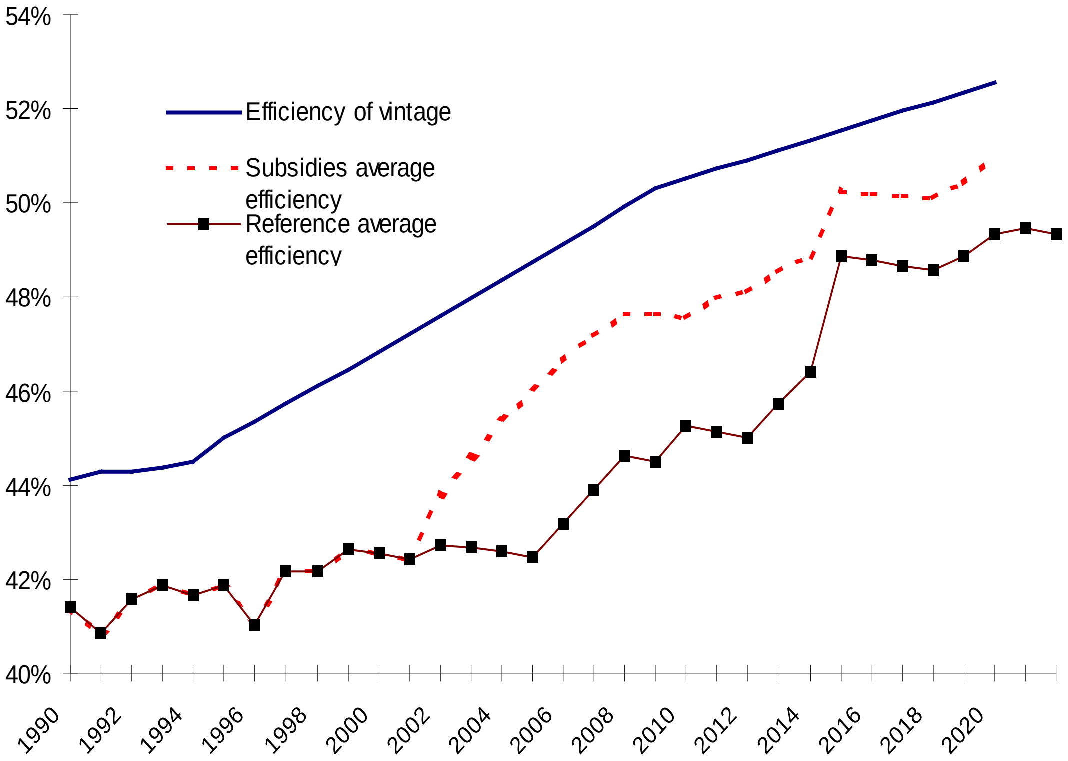

Figure 3 Fuel efficiency for major power plants in Denmark

Subsidising investment in new power plants improves fuel efficiency considerably. The effect is largest in the first years because the reference case exhibits excess capacity around 1990 and new investments in the reference are postponed to the excess capacity is reduced with the first new plants being build after 2005. The average efficiency until 2005 is based on this adjustment only improving very slowly and the gap between the efficiency of a new vintage and the average is increasing. From 2000 the subsidies result in a fast improvement of efficiency because the new plants are considerably more efficient than the average and all new plants operates at full capacity as base load plants.

The small decreases in average efficiency are caused by the discrete nature of capacity expansion (each plant is assumed to be 400MW) in combination with rising demand and capacity utilisation.

Efficiency increase corresponds to a reduction in fuel consumption for electricity production. The effect on primary energy consumption in Denmark will be greater because the new plants as the main part of the existing plants are assumed to be CHP plants. Thus the fuel for the production of heat will also be decreased. This effect will be much smaller than for electricity because heat already seen as a by-product requiring only a minor fuel input.

CONCLUSIONS

Technological progress is a critical parameter for long-term analyses of energy demand and environmental issues. Two aspects of technological progress can be highlighted: Innovation of new technologies and the diffusion of these new technologies. Vintage models can be applied for analyses of technology diffusion. This leaves the important question of fundamental innovation out, but in a short to medium term perspective the diffusion of existing technologies is probably just as important.

With technical bottom-up based models the vintage effect of new capital vintages on the average efficiency can be quantified. It is possible to include effects related to the division of production between different vintages of capital. New production capacity will be used to a relatively greater extent than older capacity.

Many countries are considering policies directed at increasing diffusion of efficient technologies. There is a wide range of possible policies of which some are best analysed in technical vintage models. 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 have the necessary detail to quantify policy outcomes.

A vintage model of electric appliances in Danish households can quantify the diffusion effect of a policy of introducing efficiency standards for categories of appliances. The policy analysis shows that a gradual tightening will produce only small efficiency gains in the short-term, but as standards are tightened towards the 5-10% most efficient versions of a given appliance that exist in 1992 the average efficiency will be increased up to 15%. The diffusion of the standards tend to delay the effect of the standard so that even when the least efficient 2/3 of the appliance versions are restricted from the market the efficiency effect is only around 3%. Some of the assumptions especially with respect to costs to consumers of policy of standards have not been addressed by this analysis.

Vintage effects are important for explaining aggregate changes in energy efficiency for a sector such as energy supply. The vintage model applied for the analysis of subsidies shows that efficiency effects can be most pronounced immediately after the investment take place because in the Danish case this is also where the gap between average and vintage efficiency is largest. The necessary investment subsidies are quite large, but the analysis does not include some other benefits related to a situation where production is actually expanded due to lower output prices and improved international competitiveness.

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