Effects of perturbations in a dynamic system – The case of Nordic power production

Niclas Mattsson, Division of Energy Technology, Chalmers University of Technology, SE-412 96 Göteborg, Sweden; phone +46 31 772 1428; fax +46 31 772 3592; niclas@entek.chalmers.se; http://www.entek.chalmers.se/index_e.html

Thomas Unger, Profu i Göteborg AB, Götaforsliden 13, SE-431 34 Mölndal, Sweden; phone +46 31 720 83 71; fax +46 31 720 83 99; thomas.unger@profu.se; http://www.profu.se

Tomas Ekvall (corresponding author), Division of Energy Technology, Chalmers University of Technology, SE-412 96 Göteborg, Sweden; phone +46 31 772 1445; fax +46 31 772 3592; tomas.ekvall@entek.chalmers.se; http://www.entek.chalmers.se/index_e.html

Abstract

We use a dynamic model of the production of electricity and district heat in the Nordic countries to investigate the effects of small changes in the Nordic power-supply system. Our aim is to improve the understanding concerning marginal effects in this system and in dynamic production systems in general. Specifically, we investigate the effects of an earlier closing of a nuclear reactor, and of increases in short-term and long-term electricity demand. Our results demonstrate that a long-term perturbation has both short-term and long-term effects. To account for short-term effects only can be a serious limitation in a study aiming at describing the effects of decisions. Marginal effects in a dynamic system are likely to involve a complex and uncertain mix of different technologies. The magnitude of the effects can be greater than the perturbation itself and remain long after it has ended. Perturbations in one production system can also have marginal effects outside this system.

Keywords: Marginal effects, energy systems, life cycle inventory analysis, methodology, Nordic, dynamic modeling

Introduction

Background

In theory, a marginal effect in a system is the infinitesimal response to (i.e., effect of) an infinitesimal perturbation (change) in this system. In practice, marginal effects can denote effects of perturbations that are small enough to be approximated as infinitesimal. This approximation is valid as long as the effects are approximately proportional to the magnitude of the perturbation. The present paper is related to marginal effects as it concerns the modeling of effects of small changes.

Marginal effects are relevant in the context of environmental life cycle assessment (LCA). They are modeled through the use of marginal data that, by definition, reflect the environmental properties of the technology where the quantity produced is actually affected by a small change in demand (Ekvall et al. 1998). The use of marginal data in LCAs has been debated. The alternatives include average data (Ekvall et al. 2001) and data representing the technology or production plant, if any, that is specified in the purchase contract (Kåberger and Karlsson 1998). However, marginal data are often considered relevant in LCAs where the purpose is to model the effects of changes (Tillman 2000). The reason is that many changes are expected to have marginal effects on, for example, the production of electricity (Ekvall 1999). In several LCAs, as well as in other types of environmental systems studies, it has been assumed that coal condensing plants deliver the marginal electricity in the Nordic countries (e.g., Pedersen 1991, Eriksson et al. 2001).

A distinction can be made between short-term and long-term marginal technologies (Weidema et al. 1999, ECON 2002). The concept of long term is defined by economists as a period long enough to allow for the replacement of capital equipment (Lipsey and Steiner 1972). Hence, short-term effects are identified through the use of an economic model where the production capacity in the system is fixed and only the utilization of capacity varies. This means that the short-term marginal technology is the technology where the utilization can be increased at the lowest variable cost. Long-term marginal effects are identified by means of a model where the production capacity is allowed to vary. The long-term marginal technology is the technology where the production capacity can be increased at the lowest total cost. This holds as long as the demand for the product is not decreasing more rapidly than the replacement rate for existing production capacity (Weidema et al. 1999). In this paper, we adopt the distinction between short-term and long-term effects. We also distinguish between short-term and long-term perturbations depending on their duration.

Ekvall et al. (1998) present the conclusions of an international panel of LCA experts, stating that the changes studied in most LCAs are assumed to affect capital investments. This indicates that long-term effects are the most relevant to model in an LCA. It has been argued that the use of marginal data is not practical because long-term marginal technology is difficult to identify. In response to this argument, Weidema et al. (1999) present a procedure for identifying the long-term marginal technology. Applying this procedure, Frees and Weidema (1998) conclude that the long-term marginal electricity in the Nordic countries will be produced either in new coal-fired plants for separate electricity production (coal condensing plants) or in new power plants for natural gas. However, Mathiesen et al. (2008) provide evidence that the uncertainty in the long-term marginal electricity is still large. Ekvall et al. (1998) argue that the long-term marginal electricity can be produced in a mix of new plants for fossil fuel and existing Swedish nuclear power plants, if the analysis takes into account that a change in electricity demand might affect political decisions on the energy system.

The specific case of marginal effects in the Nordic power system plays a significant role in the Swedish energy debate. In this context, marginal effects often denote what we call short-term marginal effects only. With this narrow definition, it is generally perceived that the marginal electricity in Sweden and its neighboring countries is currently produced by coal condensing plants (Werner 2001). In the future, it is likely to be produced by natural gas-fired plants with combined cycle technology (Gustavsson and Börjesson 1998, Werner 2001). The view that marginal electricity is currently produced by coal condensing plants is an important part of environmental arguments against the phase-out of Swedish nuclear power, against heat pumps (Seijmer 1999), and in favor of combined heat-and-power (CHP) production based, for example, on natural gas (Werner 2001). However, Lund et al. (2008) and Mathiesen et al. (2008) demonstrate that even the short-term marginal electricity can be produced by a mix of technologies, if the analysis takes into account limitations in the transmission within the Nordic power system (Lund et al. 2008, Mathiesen et al. 2008). In the Swedish energy debate, it has also been argued that the dismantling of an additional nuclear reactor would be compensated not only by coal power or natural gas but by a mix containing, for example, hydropower and wind power as well as CHP production (Swedish National Energy Administration 2001a). Such an analysis goes beyond the concept of short-term marginal effects.

Some authors take environmental aspects into account when identifying the marginal technology. Karlsson et al. (1995) state that marginal data can “almost be understood” to represent the production plant with the highest specific environmental impact. Frischknecht (1998) builds upon a concept of social cost that includes both economic and environmental costs. He then defines marginal technology as the technology with the lowest social cost on markets with an increasing demand, and the technology with the highest social cost when the total demand is falling (Frischknecht 1998). Taking account of environmental aspects when identifying marginal technologies is relevant when environmental concerns can be expected to significantly affect the choice and utilization of production plants. However, we assume here that such decisions are taken on a strictly economic basis.

Purpose, method, and reader’s guide

Our main purpose is to improve the knowledge regarding marginal effects, i.e., effects of small perturbations, in dynamic production systems in general and in the Nordic power-supply system in particular. We investigate how the electricity and district-heat production in different technologies are affected by such perturbations. Knowledge on these effects can be used, in an

LCA or similar, for estimating the environmental consequences of changes; however, we focus on the qualitative structure of the effects and not primarily on their quantitative composition. Our aim is to reveal and better understand the complexity of the matter and to identify the most important mechanisms behind the phenomena of small perturbations and their effects. We believe that this contributes to the understanding of LCA methodology as well as to the energy debate in Sweden and other countries. Hence, our paper is directed towards LCA researchers and practitioners as well as researchers and policy-makers in the energy planning area.

An additional purpose is to improve the insights into how marginal technologies can be identified. In particular, we discuss the usefulness of dynamic energy-systems models for this purpose. Energy systems analysis has a long tradition of dynamic modeling (e.g., Altdorfer et al. 1980, Unger et al. 2000). In contrast, LCA models are typically static, although there are a few exceptions. For example, McLaren et al. (2000) present a dynamic model of the energy demand of mobile phones in the UK. Gloria (2001) introduces the dynamics of the car fleet in a case study on fuel cell electric vehicles. Lund et al. (2008) and Mathiesen et al. (2008) recently used the dynamic energy-systems model EnergyPlan to investigate effects of changes in the Danish energy system.

To investigate the marginal effects in the Nordic power-supply system, we developed a dynamic model of the Nordic system for the supply of power and district heat: NELSON (Nordic ELectricity Supply OptimizatioN). We used this model to calculate the effects of various small perturbations of varied duration. In this context, a perturbation is a deviation in the boundary conditions of a pre-defined reference case. Two long-term perturbations were investigated: an earlier closure of a nuclear reactor and an increase in the long-term electricity demand caused by, for example, increased economic growth. These perturbations span several years. We also investigated a short-term perturbation corresponding to an unexpected rise in the electricity demand for a single week, for instance due to a sudden increase in electric heating. Thus, perturbations on the supply side as well as on the demand side were investigated. We believe that the perturbations and their effects are small enough to be marginal effects, although our model does not allow us to confirm that this is indeed the case, i.e., that the effects are proportional to the magnitude of the perturbation (see above).

Preliminary results from these investigations were presented at a workshop on electricity data for LCA in 2001 (Curran et al. 2005). Final results were calculated shortly after, and some of them were later presented at a conference (Ekvall et al. 2004).

Our discussion on the usefulness of dynamic energy-systems models for identifying marginal technologies is based on a sensitivity analysis of the results from NELSON. In addition, we compare the pre-defined reference case to the actual development of the energy system since the model results were produced.

The Nordic power supply system and the dynamic model are briefly described in this paper. The model results are supplemented by an analysis regarding the extent to which these results can be expected to reflect actual marginal effects in the real system. Finally, conclusions are presented regarding marginal effects both in the Nordic system and in dynamic production systems in general.

The Nordic electricity system

Power production and domestic power consumption vary significantly between the four Nordic countries Sweden, Denmark, Finland and Norway (see Figure 1). Finland and, in particular, Denmark have a large share of fossil-based power production. Norway and Sweden, on the other hand, are entirely dominated by nearly emission-free supply from hydro and nuclear power plants.

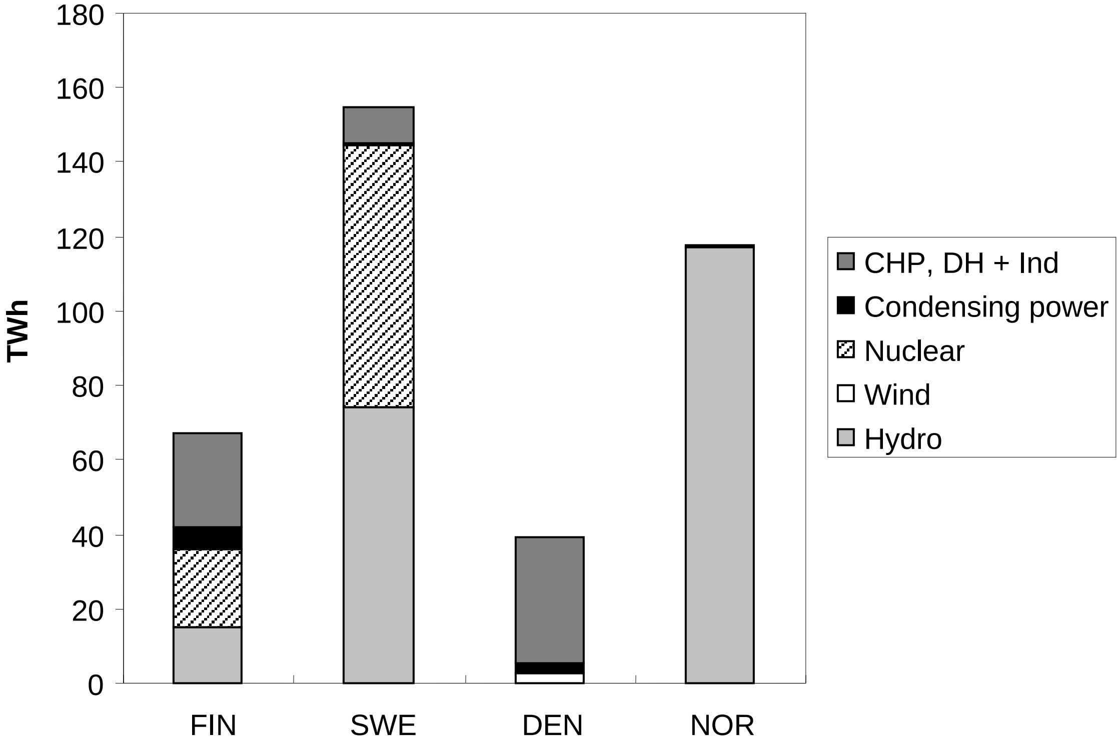

Figure 1 The power-supply systems in the Nordic countries in 1998 (Swedish National Energy Administration 1999, Ministry of Energy and Environment (Denmark[1]) 2000, Statistics Finland 1999 and Statistics Norway 2000). DH+Ind stands for electricity cogenerated with district heat plus electricity cogenerated with heat for industrial use.

Today, all four Nordic countries are integrated into a common Nordic marketplace for purchasing and selling power. This enables most electricity consumers to freely choose between power

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[1] A considerable share of the CHP production in Denmark should actually be classified as separate power production. This is due to the fact that a large share of the Danish CHP plants have flexible power-to-heat ratios, implying that only power is produced during periods with low heat demand e.g. in the summer.

suppliers. Therefore, Nordic power agents today face a common market price except when the transmission capacity between regions is insufficient to handle the exchange. The total Nordic power supply is depicted in Figure 2 according to its merit order of variable production costs.

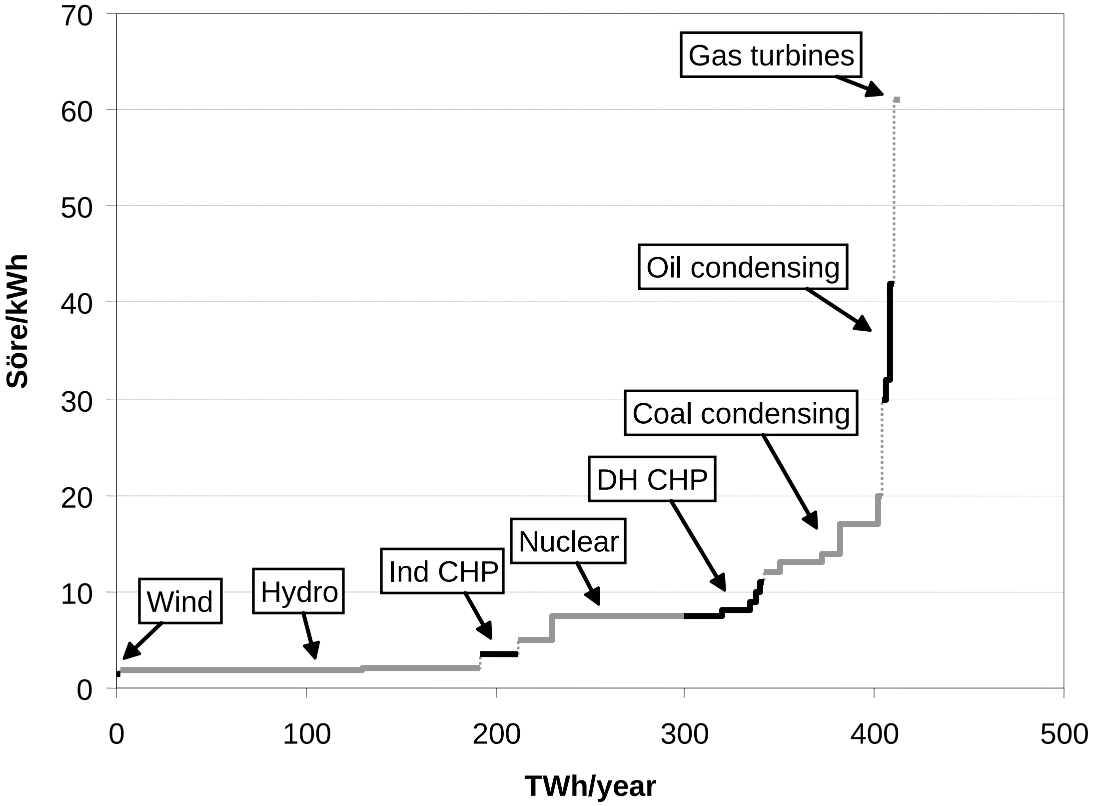

Figure 2 The supply curve for Nordic power production in 1999 shown as order of merit of variable costs (Swedish Power Association 2000; Söre 2001 = 0.1 US cents).

The demand for electricity in the Nordic countries has been around 380 TWh during the second half of the 1990s. Hence, according to Figure 2, during years with normal or high precipitation (corresponding to a total hydro output of about 170 TWh and 190 TWh respectively), the technology where utilization can be increased at the lowest variable cost is coal-condensing power. During years with little precipitation the supply curve accordingly shifts to the left in Figure 2, which might lead to full utilization of coal-condensing and some utilization of even more expensive technologies, such as oil-fired condensing units. This outline is the basis for the conventional argument that under normal conditions the marginal electricity is supplied by coal condensing units.

In this context it can be noted that the immediate response to quick changes in electricity demand is often a change in electricity production from regulated hydropower. This immediate response can be denoted quick marginal electricity and is distinguished from short-term as well as long-term marginal electricity (ECON 2002). Since the available amount of energy from hydropower is limited, increased hydropower production on one occasion means that less hydropower is available for future use. A quick change in electricity demand is unlikely to affect total hydropower production, but only to shift it in time.

The model and key assumptions

Model description

Our analysis of the Nordic electricity system is based on the dynamic, optimizing model: NELSON. This model follows in the tradition of bottom-up energy system models such as MARKAL or EFOM (Fishbone and Abilock 1981; Finon 1979). These large-scale technology-oriented linear programming models optimize the development of the entire energy system from fuel extraction and import to end-use. They produce the most cost-efficient solution that satisfies exogenous demand subject to technological assumptions (e.g. investment cost of technologies, fuel cost development, thermodynamical efficiencies, availability, etc.). The models are usually multisectorial (includes residential, industry, transportation) and often multiregional. Investment planning decisions are generally made with perfect foresight for the entire time horizon, typically 30-50 years.

Optimizing models have been used for a normative purpose: to identify the most cost-efficient development of the system as a basis for planners. Such use of the models is important when the energy system is under the control of a government or a single company. It is less relevant on the Nordic electricity market, since this market is not under the control of a single supplier. Instead, we use the optimizing model to generate conditioned forecasts. In our study, NELSON is used to simulate the future behavior of the energy system, given a series of conditions: that the competition on the energy market is efficient, that the decision-makers are economically rational, that our fuel price assumptions are correct, etc. These simulations, or conditioned forecasts, allow us to investigate the foreseeable consequences of perturbations in the energy system.

NELSON is a linear programming model of the Nordic systems for electricity and district heating supply. These systems are connected, both in reality and in the model, through CHP plants and through district heat production in heat pumps and electric boilers. End-use sectors and associated demand-side technologies are not specified in NELSON. Instead, demand for power and district heating are input data to the model, collected from Unger et al. (2000). The optimization is performed with limited (imperfect) foresight, using a time-stepped procedure with a nine-year rolling time horizon (see Appendix). This optimization procedure was chosen to better correspond to decision-making on a deregulated market and also to provide a more realistic description of the utilization of hydro resources. The objective of each sequential optimization is to minimize the total discounted cost of the entire Nordic electricity and district heating systems during the current time horizon.

The four Nordic countries (Sweden, Norway, Denmark and Finland) are each modeled individually. Interregional trade of electricity is possible but is limited to the transmission capacity that existed in 2000. The model spans the years 2000-2050, using 17 time periods of 3 years. Each time period is in turn divided into 52 (weekly) intervals.

The technological database in NELSON includes 15 technologies for power generation, nine technologies for district heat production and an additional eight CHP technologies. Technology data and other input assumptions in the model coincide to a large extent with those used in the NORDLEDEN project (Unger et al. 2000). Technological development is considered using exogenous investment cost reductions of new power technologies.

The supply of natural gas to the Nordic energy system in NELSON is unbounded. Transmission and distribution grids for natural gas are not explicitly modeled, but their costs are accounted for by a component of the fuel cost. Bio energy is described using only one fuel cost class. Wind power is disaggregated into one offshore and two onshore resource classes. Each class is associated with an upper capacity limit. Nuclear power in Sweden can be utilized throughout its natural lifetime, but no reinvestments or new investments are allowed. New nuclear power investments are only permitted in Finland.

Hydropower availability and regulation have a crucial influence on the dynamics of the Nordic energy system. The availability depends on precipitation. In NELSON, precipitation variations are cycled in the 5-period sequence: normal, normal, dry, normal, wet. Also, a typical (weekly) precipitation pattern is used within each period. The model itself has one aggregated water reservoir per country.

A basic CO_2 tax is placed on heat production corresponding to the current average Nordic taxation levels. In addition, restrictions on total CO_2 emissions can be used to produce low-CO_2 scenarios. These restrictions are placed on total emissions from electricity and district heat in all four Nordic countries in each 5-period precipitation cycle.

The model is written in AMPL and is solved with CPLEX 7.0 in 10 minutes on a Pentium III-700.

Model limitations relevant to the current study

The fact that energy demand is exogenously given means that the model can only describe marginal effects on supply-side technologies. Responses in the real system can include marginal effects on demand-side technologies or reduction of energy demand due to economic feedback. Indeed, corresponding studies of perturbations using the MARKAL-NORDIC model (Unger et al. 2000) indicate that marginal effects also appear on the demand-side. For instance, a perturbation consisting of a withdrawal of supply capacity is likely to lead to a substitution of electricity on the demand side as well as substitution of power generation. The limitation of omitting the demand side affects the results of our study, but should not have any bearing on the general conclusions. If the model allowed effects on the demand, the magnitude of the effects on the production system would be lower, but the composition of the effects on the production system would be essentially the same.

The political boundary conditions of the energy system are also exogenously given. This means that the model does not allow the perturbations to affect political decisions concerning, e.g., the phase-out of Swedish nuclear power. This limitation is considered in our conclusions.

The lifetime of all power plants in the model is fixed. Neither premature dismantling nor lifetime extension of existing power plants is allowed. Therefore, all investment responses to perturbations have fixed durations.

In the model, hydropower capacity is fixed at current levels. Hydropower investments will therefore not appear among the marginal effects. In contrast, results from the Swedish National Energy Administration (2001a) indicate that, in reality, marginal effects can include new investments in small-scale hydropower plants and efficiency measures in existing large-scale hydropower plants.

Results and analysis

In this section, results from model runs are presented and discussed briefly. The overall development of the Nordic power system over time is crucial to its response to perturbations. In Figure 3, the development over the next 50 years according to the NELSON model is shown. This result is of course sensitive to input assumptions.

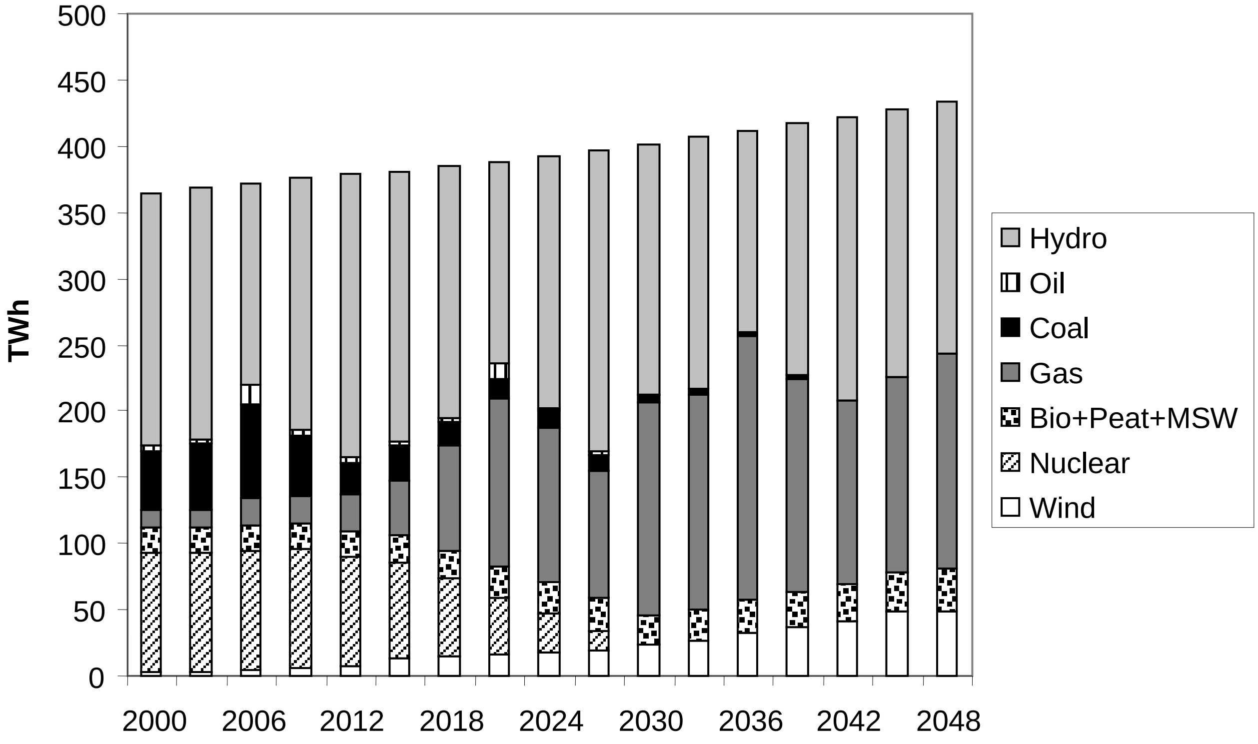

Figure 3 Nordic power production in the reference case. The fuel categories are defined as electric output in TWh using a specific fuel or means of production (e.g. wind).

It can be observed that gas-fired power plays an increasingly vital role in the model due to assumptions of low gas-price and unlimited gas transmission capacity. Variations in hydropower are due to variations in precipitation, as previously discussed. Nuclear power disappears before the year 2030. In Sweden this is a political boundary condition, as mentioned above. In Finland it is because nuclear power is not economically competitive with the assumptions made in the modelling. Here the model has already been proven wrong: Finland is now expanding their nuclear power capacity.

The case in Figure 3 is defined as the reference case since it does not contain any of the perturbations to be studied. Introducing a perturbation into the electricity system will yield a new model result. If the perturbation is small compared to the system, the overall development will be quite similar to the reference case. However, the *difference* in power production over time between these two cases is by definition the response to that specific perturbation plus the perturbation in itself. All changes observed in the difference between the perturbation case and the reference case, are due to the decision that causes the perturbation.

Reduction in nuclear power

The first perturbation analyzed is the withdrawal of 600 MW of nuclear power capacity in Sweden in 2003. The magnitude of the perturbation corresponds to the size of the Barsebäck II plant in Southern Sweden. This specific plant is currently subject to political debate regarding an early shutdown. Since we assume a total technical lifetime of 40 years for nuclear power, the withdrawal in question occurs 15 years before the technical lifetime of the capacity is reached. Thus, the duration of the perturbation is 15 years, which we regard as long-term. The corresponding effect of this perturbation according to model runs is shown in Figure 4.

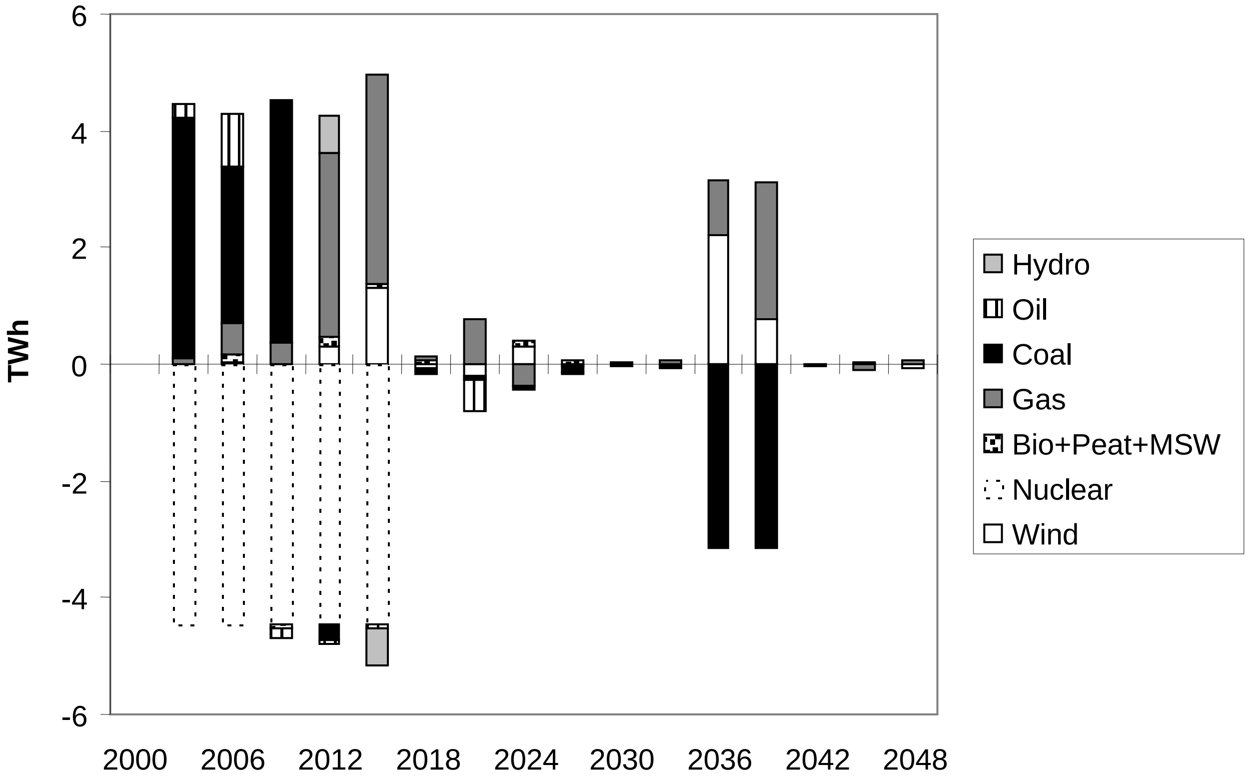

Figure 4 The effect in the Nordic electricity system of an early shutdown of 600 MW of nuclear power in Sweden. The perturbation is shown as dotted bars. The figures are expressed as electric output in TWh using a specific fuel or means of production (e.g. wind).

In Figure 4, the perturbation itself is expressed as an annual reduction in nuclear power corresponding to roughly 4.5 TWh. As a response, the loss of nuclear power in the model is replaced by a mix of other technologies. These are shown as positive bars in Figure 4. The negative bars for technologies other than nuclear power mean that, while certain power options increase, others may decrease compared to the reference case. The complexity in the model response is even greater than indicated by Figure 4, since it presents different technologies aggregated into fuel classes. For instance, coal power in Figure 4 includes condensing power units as well as CHP units.

This long-term perturbation apparently gives rise to both short-term and long-term effects in the model. The short-term effects occur during the first three-year period of the perturbation, i.e. before any investments can be made in response to the perturbation. Hence, they concern the utilization of existing technologies - mainly coal-condensing power plants. From the second three-year period of the perturbation, effects on the investments in new power plants occur in the model. These long-term effects include earlier investments in CHP plants for coal and natural gas as well as wind power. Figure 4 also indicates that the long-term effects include a delay in some investments. Note that Figure 4 only presents the difference in electricity production that is caused by the perturbation. When the perturbation cause the investment in a specific technology to be affected in time but not affected in size, this technology appears in Figure 4 during the time period that the investment is shifted in time. In subsequent periods, the electricity production from this technology is the same as in the reference case, which means that the technology does not appear in this part of Figure 4. Note also that long-term effects occur in the model even long after the perturbation has ceased. Investments that are shifted in time, as a response to the perturbation, can give rise to consequences when these investments in turn are to be replaced.

The long-term effects are very sensitive to the assumptions in the model. The fact that a withdrawal of nuclear power causes a delay in investments in, e.g., wind power, is even contra intuitive. These aspects of the model results cannot be validated. But in several important aspects the model response in Figure 4 resembles how we would expect the real energy system to react to a shift in time in the phase-out of a nuclear reactor:

- Although such a shift in time is not made without warning, the power suppliers would not be able to immediately replace the nuclear power with other capacity for electricity production. When an investment decision is made it can take 5-10 years before the power plant has been constructed and starts delivering electricity. Instead, the short-term effect is likely to be increased use of utilization of existing production capacity at coal condensing plants (see Background).
- Wind power is currently expanding in the Nordic countries. If the phase-out of a nuclear reactor contributes to keeping electricity prices up, this is likely to stimulate a more rapid expansion of this technology.
- Combined cycle gas technologies are among the most competitive new supply options, and investments in CHP plants with this technology are currently considered in the Nordic countries. The phase-out of nuclear reactors can speed up this process.

Our model results as well as our discussion demonstrates that a shift in time in the phase-out of a nuclear reactor can be expected to affect several technologies such as coal-condensing power, gas CHP and wind power. Our results confirm the results presented by the Swedish National Energy Administration (2001a), except for the effects on hydropower investments.

The phase-out of 600 MW nuclear capacity affects not only the electricity production. The response in the district heating sector to this perturbation is shown in Figure 5. During the first time step of the perturbation (in 2003), the district heating sector is not affected. This is because the perturbation in the power system in the short-term perspective is entirely met by condensing technologies that are not linked with the district heating sector. In the long run, however, the district heating system responds through an increased use of gas, coal and biofuels, mainly in CHP plants. As illustrated in Figure 5, these fuels replace other options, including electric heating. Again, the results are very sensitive to the assumptions in the model. However, it is obvious that the effects of a perturbation in the electricity system may propagate to other, connected systems such as district heating systems.

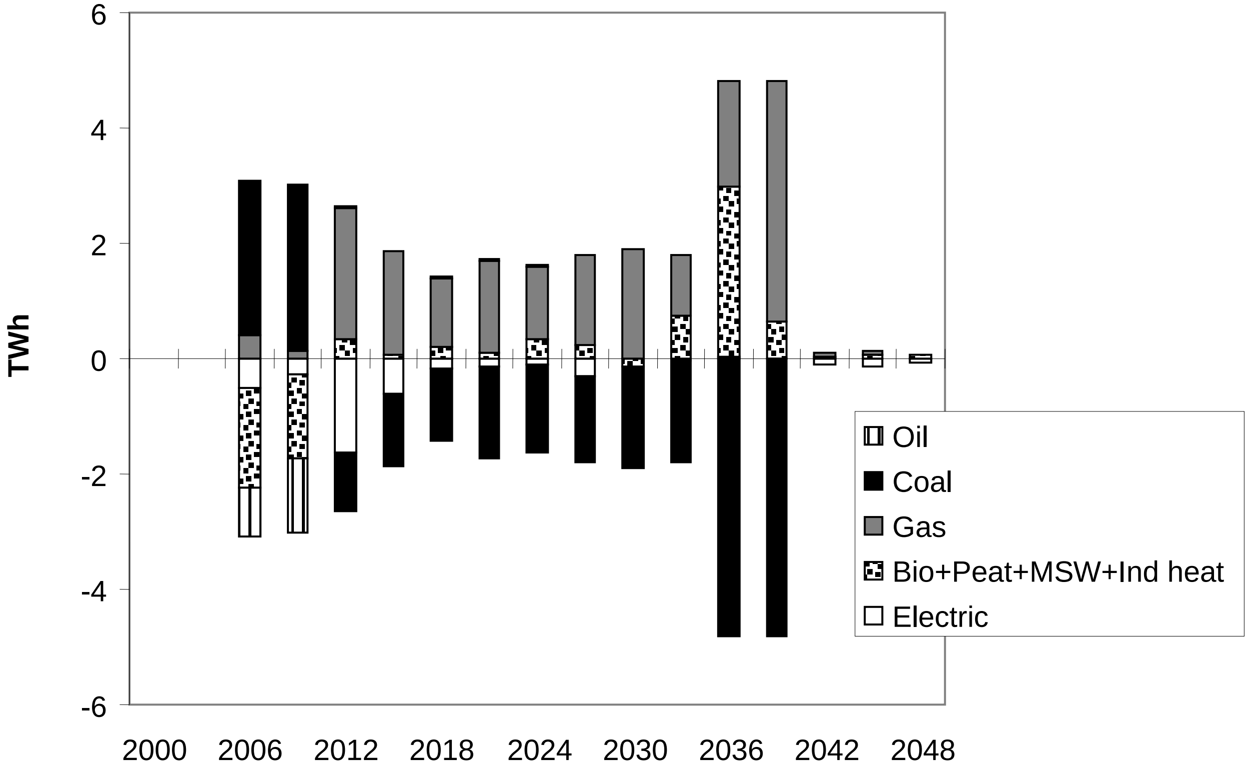

Figure 5 The response of the district heating supply to an early phasing-out of 600 MW of nuclear capacity in the Swedish power supply. The figures are expressed as TWh district heating output divided into fuel categories. District heating from electricity is primarily produced in heat pumps. Hence, the effect on electricity demand is a fraction of the effect on electric district heating.

Increased long-term demand

The second perturbation investigated in this study is an annual increase in power demand of 1 TWh throughout the entire modeling period. The additional load is constant, i.e. equally large in each week. This long-term perturbation roughly corresponds to the increase in industrial electricity demand due to one year of economic growth in Sweden[2]. Its effect on the power-supply system is presented in Figure 6.

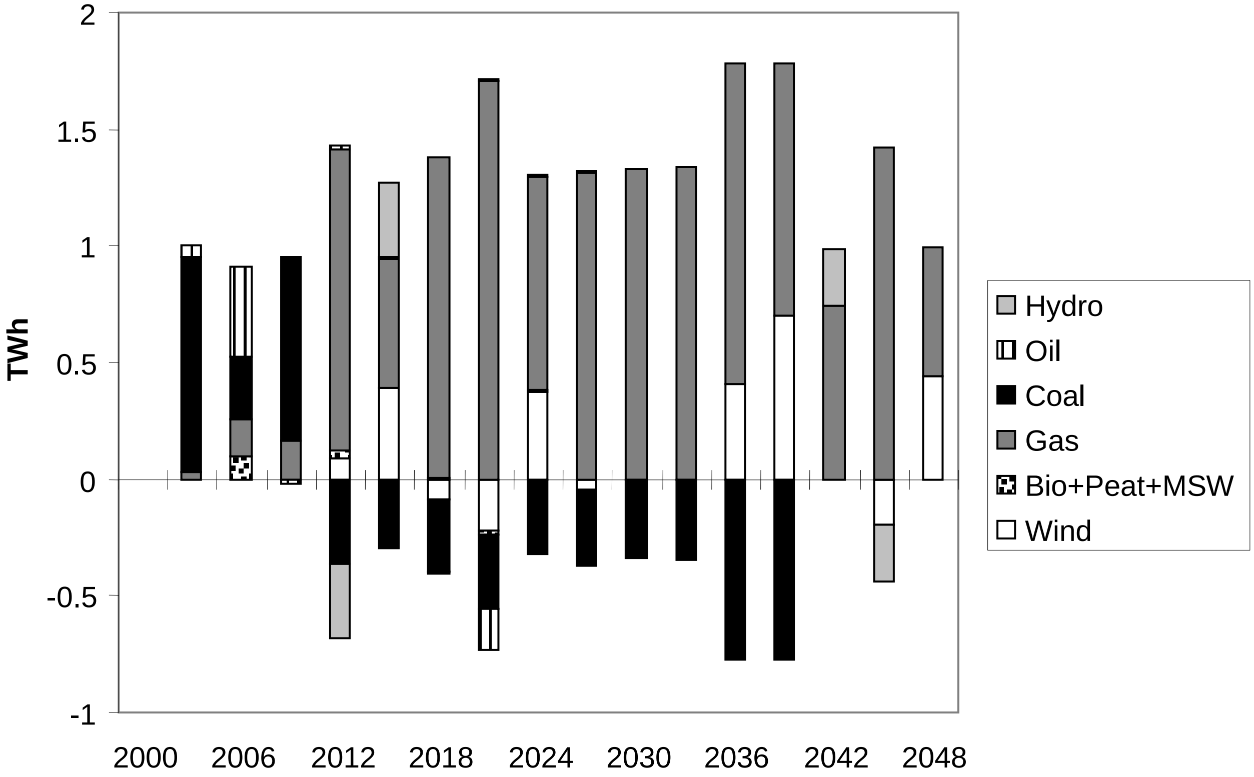

Figure 6 Effects of a long-term annual perturbation of 1 TWh. The figures are expressed as TWh electric output divided into fuel categories.

Again, the complexity of the perturbation response is apparent. It can be noticed that the effect of a long-term increase in demand shown in Figure 6 resembles the effect of a reduction in nuclear power supply (c.f. Figure 4) during the periods in which the perturbation is active. It can also be observed that, during some time periods, responses to the perturbation are greater than the perturbation itself. This can be seen in the time periods following 2012, where additional

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[2] The difference in industrial electricity use due to economic growth was approximately 1.4 TWh between 1999 and 2000 in Sweden (Swedish National Energy Administration 2001). This also corresponds to the electricity use in a very large industrial site.

electricity from gas exceeds the 1 TWh annual increase in demand. The net increase is still 1 TWh due to a corresponding decrease in electricity from e.g. coal. In the model, these changes occur in the CHP sector. The increase in electricity demand combined with a constant demand for district heating changes the relative profitability of gas and coal CHP in favor of the technology with the highest power-to-heat ratio, i.e. gas. A similar effect can also be expected in reality.

We performed a sensitivity analysis on three parameters that can significantly affect the response to a long-term increase in demand. The parameters chosen were 1) The lifetime of existing coal power, 2) Natural gas prices and 3) Future climate policy. Figure 7 summarizes these results. For simplicity, the perturbation responses have been aggregated over time and normalized to the size of the perturbation.

The lifetime of existing coal power is of great importance because coal is the technology on the margin in the existing system. The utilization of existing coal power will dominate perturbation responses until significant investments are made in the model. When this occurs depends on how the electricity demand develops and when existing power plants are phased out due to ageing. In bar two of figure 7, the lifetime of existing coal power has been extended indefinitely. This postpones new investments in gas power until demand for electricity exceeds existing capacity and leads to a considerably increased utilization of coal, as seen in bar two.

Future gas prices are crucial because combined cycle gas technologies are among the most competitive new supply options and fuel costs are a dominant part of total costs for gas power. In the reference case, we assumed a gas price of 85 SEK/MWh at the Nordic border. This price remains constant throughout the entire modeling period. As illustrated in Figure 3, these assumptions combined with comparatively low investment costs make gas power the new technology of choice. In bar three of figure 7, the gas price is raised linearly to 115 SEK/MWh in 2050. This decreases the competitiveness of that fuel and changes the effects of perturbations accordingly. When the NELSON model was completed, at the beginning of this decade, a gas price of 115 SEK/MWh in 2050 was a high estimate, since natural gas prices were stable from the year 1995 to 2000. However, recent developments make it a very low estimate: the price of natural gas has more than doubled from the year 2000 to the first half of 2008, i.e., as early as the third out of 17 3-year periods. The price paid by power plants in now is nearly 250 SEK/MWh (Statistics Finland 2008).

Sensitivity to climate policies was analyzed by applying a common CO_2 emissions cap on the Nordic district heating and power systems. The cap corresponds to an emission reduction that grows linearly in strength to a 50 percent reduction in 2050 compared to the base year 2000. The Swedish National Energy Administration (2000) claims that future climate policy can reduce the share of coal power in effects from perturbations. This statement is supported by our model results, which can be seen in the far right-hand bar in Figure 7. Due to the emissions cap, the carbon content of the perturbation response mix is comparatively low. Instead, bio-fuelled power and Finnish nuclear power are important parts of the response. There is still some fossil content in the mix, because the emissions cap in the model covers the district heating system as well as the power system. This means that some shifting of CO_2 emissions between the district heating system and the power system can occur.

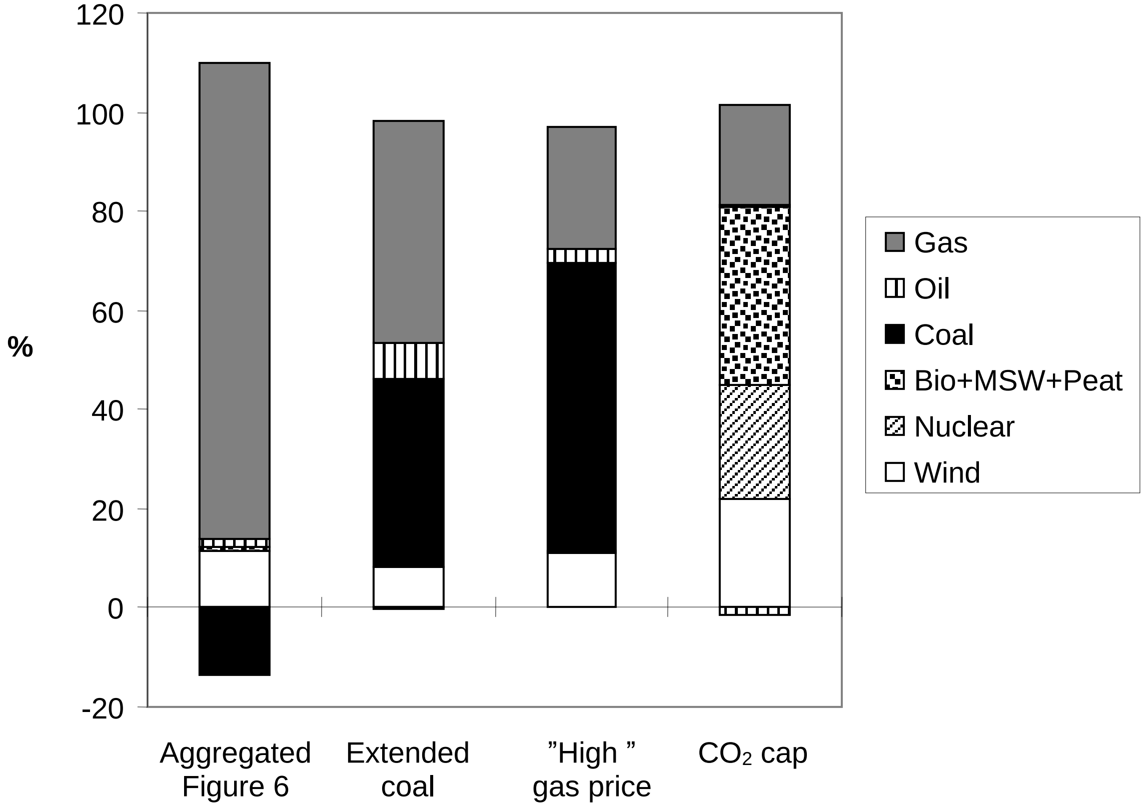

Figure 7 Sensitivity study: the mix of electricity production induced by a 1 TWh/year perturbation in the reference case (c.f. figure 6), a case with extended lifetime of coal power plants, a case with higher gas prices, and a case with a cap on total CO_2 emissions from the Nordic production of power and district heat.

Increased short-term demand

Hitherto, we have analyzed effects from long-term perturbations. We now investigate the short-term effects of 17 different short-term perturbations. Each of these is introduced in a different 3-year period of the model. In other aspects, the perturbations are identical: they consist of an increase in electricity demand of 0.1 TWh during a single winter week[3]. The model system can only respond to this increase by changing the utilization of existing capacity. This makes it possible for us to identify the short-term marginal technology in each of the 17 time periods of the model.

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[3] As a comparison , the difference between the two weeks with the highest load in the model is roughly 0.3 TWh. Thus, the increase in electricity demand by 0.1 TWh corresponds to the effect of a winter week being somewhat colder than in the reference case.

The results are presented in Figure 8. They support the common belief, as presented in the introduction, that coal condensing power is currently on the short-term margin in the Nordic power supply. After the first decade, gas-fuelled power dominates the short-term margin. There are also interactions with the district heating system. This can be seen in 2012, where the power system response is significantly smaller than the perturbation. The difference in this case is handled by a corresponding decrease in district heating supply from heat pumps. Two years, 2006 and 2021, differ significantly from the others. These are both dry years, so perturbations lead to other effects than in the wet and normal years surrounding them.

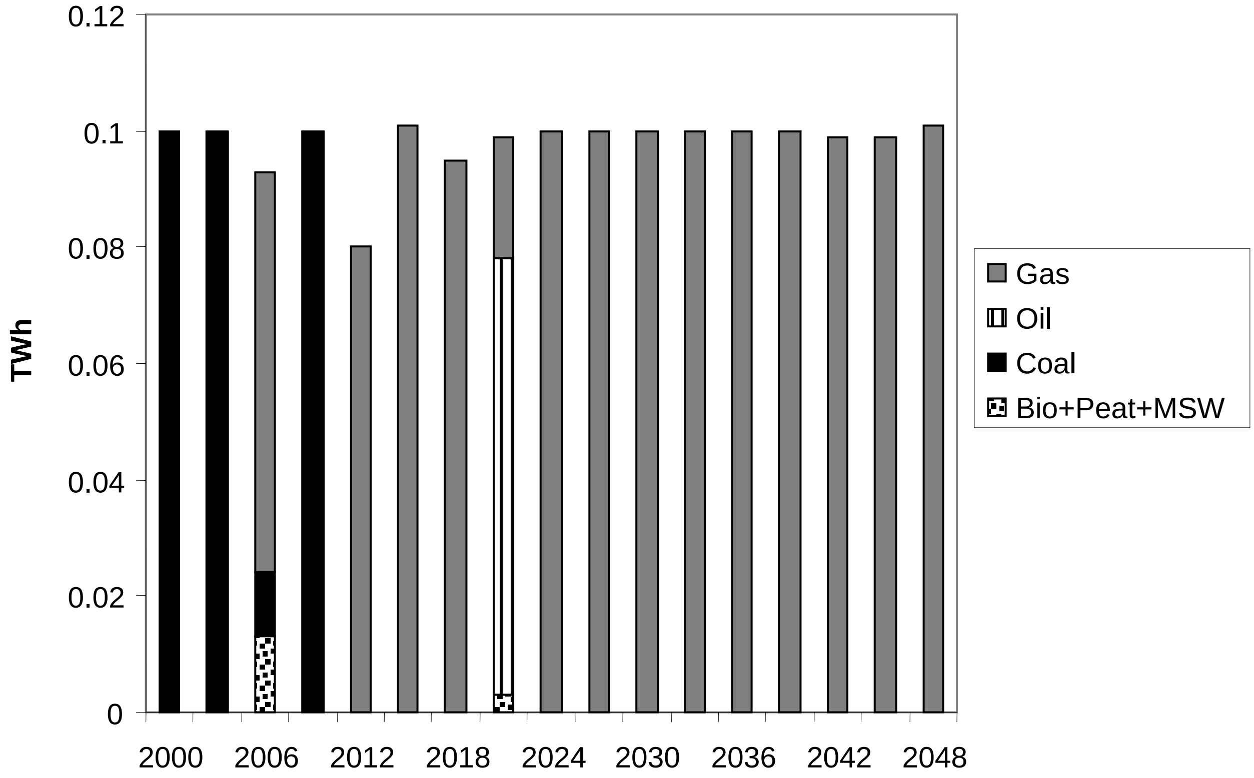

Figure 8 Short-term effects of the 17 short-term perturbations.

Discussion and conclusions

The Nordic electricity production system is dynamic. It can be expected to change over time also in the reference case, i.e., without the perturbations investigated in this study (see Figure 3). When small but long-term perturbations are introduced, the electricity system develops slightly differently, compared to the reference case. The effects of such perturbations can apparently involve several technologies. A long-term perturbation has a short-term effect that takes place before the production capacity can adapt to the perturbation. In the current Nordic electricity system, the short-term effect is increased utilization of existing coal power plants. The long-term perturbation also has long-term effects, that is, effects on investment decisions. Due to the dynamics of the electricity system, decisions on investments in different technologies (gas CHP, wind power, etc.) are on the agenda at different points in time. For this reason, a long-term perturbation can affect investment decisions in several technologies. For instance, future investments in wind power or CHP plants may be shifted in time.

The magnitude of effects can be greater than the magnitude of the perturbation. The effects may also continue long after the perturbation has ceased. This can occur, for example, when an investment and, hence, the lifetime of a new power plant is shifted in time (see, e.g., Figure 4). A perturbation in the electricity production system can affect the production system for district heating (see Figure 5). Since the perturbation is likely to increase the electricity price, it can also reduce the electricity demand and, indirectly, increase or reduce the demand for other products.

Our results support the view of, for example, Werner (2001) that the short-term marginal electricity in the Nordic electricity system is based on coal today and natural gas in the future. Our model is not adequate for investigating possible long-term effects of short-term perturbations. Such effects can be expected only when the perturbation affects the expectations concerning the future development of the system - in other words, when the decision-makers are not aware that the perturbation is short-term only. In such cases, even a short-term perturbation can have complex marginal effects.

A similar behavior can be expected in many other production systems: a single, long-term perturbation will have both short-term and long-term marginal effects. If investment decisions in different technologies are on the agenda within the time frame of the foreseeable effects, the long-term effects themselves are likely to be complex, i.e., involving several technologies. We expect that perturbations in a production system can also have marginal effects outside this system. The reason why many authors assume that the marginal effect only involves a single technology can be that their (implicit or explicit) model of the production system is static and that they focus on the short-term or long-term marginal effects only.

Energy systems analyses and LCAs often account for short-term effects only (see Background section). This is also true for the dynamic modelling of Mathiesen et al. (2008). However, the long-term effects can be a dominant share of the total effects and concern technologies with environmental properties that are completely different from coal power. The exclusion of long-term effects can clearly be a serious limitation in an analysis, if the aim is to describe the effects of decisions. If energy or environmental debates are based on such studies, there is an apparent risk of biased debates.

A dynamic model is required to investigate the complex marginal effects. However, LCA models are typically static. To make it possible to account for complex marginal effects in an LCA, the results from the dynamic model must be translated into a static data format. In principle, this can be achieved by calculating the sum totals of the perturbation and dynamic effects up to a specific point in the future, which becomes a system boundary in time. The sum total of effects can be divided by the sum total of perturbation to obtain static data on the complex marginal mix of technologies. This is how the dynamic results in Figure 6 have been translated into the first bar in Figure 7.

NELSON results depend heavily on our assumptions regarding, for example, the time frame of the perturbation, the future price of fuels, technological development and restrictions on CO_2 emissions (see Figure 7). Our results illustrate that the marginal electricity mix can include elements of coal condensing, CHP fuelled with coal, natural gas as well as renewable fuels, and/or wind power. The actual composition of this mix, in terms of numerical values, is highly uncertain. This sensitivity to boundary conditions and other assumptions is not unique to NELSON, as demonstrated by, e.g., Mathiesen et al. (2008). We expect a similar sensitivity from any dynamic optimizing model, when it is used for identifying marginal effects.

Recent developments also give NELSON wrong in the results as well as in underlying assumptions. In the model of the reference case, Finnish nulear power is continously reduced and disappears before the year 2030; in reality a new plant is currently under construction. When the model was constructed, a natural gas price of 115 SEK/MWh in the year 2050 was assumed to be a high estimate. The real price in 2008 is already more than double that level. The errors in the NELSON model were not caused by unrealistic assumptions. The price of natural gas had been stable for several years when the model was constructed. Instead, the errors illustrate just how difficult it is to predict the future. This problem is also common to other long-term dynamic optimizing models.

The large uncertainties in our model results seemingly confirm the view that the long-term margin is difficult to specify (see Background). However, this is not necessarily a valid argument against the use of long-term or complex marginal data in LCAs and similar studies. When marginal changes are expected, only marginal data can convey information on the effects of these changes. Some of the uncertainties can also probably be reduced through improvements in our model, database and scenarios. Further research and development is required to investigate the extent to which these uncertainties can be reduced, and how they can be dealt with in the context of LCA and other environmental systems studies.

As indicated in the introduction, our purpose was to study the qualitative structure of the effects and not to present quantitative results. However, LCAs and similar studies require quantitative input data on electricity production, and our model results provides some basis for recommending what data to use to model Nordic electricity production in LCAs where the purpose is to model the effects of changes:

- As a first approximation, assume that the marginal electricity is produced in CHP plants or condensing power plants utilizing natural gas. Natural gas CHP is an important element in most of our model results. The environmental performance of natural gas is also in between the environmental performance of coal and wind power in important aspects (notably CO_2 and NO_X emissions).

- For a more thorough analysis, use two electricity scenarios based on the results presented in Figure 7 for “high” gas price and CO_2 cap. The difference between these results is very large, which mean that they can indicate the magnitude of the uncertainty in the electricity mix.

- The most thorough alternative is to run a model of the energy systems affected with the perturbation that is investigated in the specific LCA. As indicated by the discussion above, a generous sensitivity analysis is then required to indicate the magnitude of the uncertainty that still remains.

Appendix

The sequential optimization was performed using the following procedure.

Each time period spans three years. Suppose current time period is T:

1. precipitation in period T is known, precipitation in periods T+1 and T+2 are assumed to be normal
2. production capacity is fixed up to (and including) T, other model variables are fixed up to (and including) T-1
3. solve the model for periods T to T+2
4. fix resulting capacity utilization (primarily power generation) for period T
5. change future precipitation assumptions: actual precipitation in the model during periods T+1 and T+2 is now known
6. resolve the model for periods T to T+2 to obtain investment decisions
7. assign T := T+1 and repeat procedure from 1.

Implications:

- The model plans two periods into the future.
- All investment decisions are made one time period in advance (implying a 3 year construction lead time) using accurate future precipitation assumptions. This guarantees that sufficient capacity is available when dry years occur. How this will be guaranteed in the real future system has yet to be decided.
- Decisions of how to utilize hydropower and other technologies are made assuming normal future precipitation. Since this assumption is often incorrect, the foresight is imperfect. In other words, the model includes an element of surprise.

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