STOCKHOLM SCHOOL
OF ECONOMICS
THE ECONOMIC RESEARCH INSTITUTE

Power production and the price of electricity: An analysis of a phaseout of Swedish nuclear power

Bo Andersson and Erik Hådén

Working Paper No. 105
February 1996

Working Paper Series
in Economics and Finance

Power production and the price of electricity: An analysis of a phaseout of Swedish nuclear power.

by

Bo Andersson and Erik Hådén*
Stockholm School of Economics
Box 6501
S-113 83 Stockholm, Sweden

February, 1996

Abstract

In this paper the effects of a phaseout of Swedish nuclear power combined with different CO_2 emission goals, are studied. The vital relationship between the national electricity market and the regional markets for heating is modeled in detail in a dynamic partial equilibrium environment. It is shown that phasing out nuclear power while restricting future CO_2 emissions to the 1990 level implies a significant increase in electricity prices and a substantial loss in welfare.

Keywords: Electricity, Nuclear phaseout, Dynamic partial equilibrium, CO_2 emissions

JEL Classification: Q 48, Q 38, L 79

---

* The authors wish to thank Lars Bergman for helpful comments and suggestions. The basic modelling work in this study was made in connection with a report on Swedish energy policy by William D. Nordhaus (see Nordhaus (1995)). Financial support from Sydkrafts Forskningsstiftelse, Swedish National Board for Industrial and Technical Development (NUTEK), and Nordic Energy Research Program is gratefully acknowledged.

1. Introduction

In Sweden energy policy in general and the electricity market in particular has been in the focus of attention for some time. The main reason being a referendum held in 1980 concerning the future of Swedish nuclear power. Following the referendum the Swedish parliament decided that no further nuclear reactors would be licensed and that the existing nuclear reactors should not be permitted to operate beyond the expected lifetime of the latest reactor installed. A year that was explicitly pointed out was 2010. To complicate matters further there are three additional decisions taken by the Swedish parliament that in fact are closely related to the issue of phasing out the nuclear power.

First, concerns about global warming, the greenhouse effect, have brought the parliament to commit Sweden not to increase CO_2 (carbon dioxide) emissions above 1990 levels. If nuclear power is phased out, it would probably be economical to replace some of the electricity production by fossil-fuel-powered electricity. But this would lead to higher CO_2 emissions, which would threaten the CO_2 commitment.

Secondly, the parliament has decided that the rivers and river stretches that are unharnessed, i.e. excluded from hydro power development, will remain protected in the future. Obviously this excludes hydro power, which today makes up for about half the Swedish electricity production, as a large-scale substitute for nuclear power.

Thirdly, in 1991 an agreement by a majority of the parliament added one very broad, yet critical, policy objective. It stated that one major purpose of energy policy in Sweden was to secure the short-term and long-term supply of electricity on internationally competitive terms. In the agreement the parties emphasized that secure supplies of electricity, reasonably priced, were an important condition for the international competitive strength of Swedish industry. If the nuclear power is to be phased out and the possibility to replace it by the relatively inexpensive techniques of fossil fuel power and hydro power are excluded as a result of the CO_2 commitment, the price and supply of electricity will most certainly be affected.

The purpose of this paper is to study the effects of different policy scenarios with respect to Swedish energy policy, specifically issues concerning a nuclear phaseout and restrictions on CO_2 emissions. This is done by the means of a dynamic partial equilibrium model of the Swedish energy market where the interdependence between the electricity market and the markets for heating is modeled explicitly. As a basis for our scenarios we use the restrictions on future energy policy imposed by the Swedish parliament.

Swedish energy policy has been studied thoroughly on several occasions. The latest example is a study by Nordhaus (1995) where he focuses on the effects of a nuclear phaseout and the related CO_2 commitment issue. The major difference between our approach and the one in Nordhaus' study is that his is more macro-oriented. The model we use is more disaggregated and focus on the electricity market in detail and is intended to capture the important interrelation between the heat markets and the electricity market. The issue of a Swedish nuclear phaseout has also been studied by Amundsen et. al. (1994)[1]. They use a static multi country model where the production facilities in different countries and the transmission possibilities between different national electricity grids are taken into account when the effects of a phaseout of Swedish nuclear power is discussed. The model we use allows for imports of electricity, although this is modeled in a less sophisticated way than in Amundsen et. al.. Instead of focusing on the international dimension, as in their study, our model focuses on an inter temporal dimension and the electricity market's development over time following a Swedish nuclear phaseout.

The remainder of the paper is structured as follows. The next section gives a brief description of the Swedish electricity and heat markets. In section 3 the model is presented. This is followed by a section were a Base Case is introduced. In section 5 different policy scenarios are described and analyzed. Section 6 contains a sensitivity analysis. Some concluding remarks are then made in the final section.

2. The Swedish Electricity and Heat Markets

An interesting feature of the present electricity production in Sweden is that hydro and nuclear power together account for more than 95 % of total power production, and that the annual nuclear production is approximately equal to the annual hydro production. The remaining production comes from plants fired by either coal, oil, natural gas or biomass. On the demand side one can observe that more than 20 % of the electricity is used for heating purposes. The electricity used for heating is equally divided between direct electric heating and waterborne heating.

[1] The report in the reference list contains a description of the model in question. The study of a Swedish nuclear phaseout is in Norwegian. A complete reference to this study can be obtained at request.

In the case of district heat production the plants are either cogeneration plants, heat plants (ordinary combustion), heat pumps, electric boilers or industrial backpressure. It should be pointed out that this sector may produce large amounts of electricity from the cogeneration plants when this is profitable, i.e. when electricity prices are high relative to the alternatives. When electricity prices are low this sector may instead, at short notice, swing over to become a large net consumer of electricity by using for example electric boilers to produce heat. The supply of district heating is restricted to certain geographically limited regions.

The structure of the power producing firms on the Swedish electricity market is characterized by a high degree of concentration. The largest firm, state owned Vattenfall, account for more than 50 % of total production, and the second largest firm, Sydkraft, is close to 25 %. Together the ten largest producers make up for more than 95 % of total power production.

3. The Model

Our model, DELMARK, is a dynamic partial equilibrium model. It originates from a static model, ELMARK, documented in Carlsson (1988). In DELMARK six energy markets in Sweden are explicitly treated: One nation-wide electricity market, three regional markets for district heating, and one market each for light oil and heavy oil, respectively. Through the model, equilibrium prices and quantities can be obtained for each of the markets. In comparison to energy models such as MARKAL (see for example Fishbone and Abilock (1981)) and MESSAGE (see for example Messner (1984)), it is important to point out that DELMARK is a *market model* focusing on equilibrium prices and volumes of commercially traded energy such as electricity, and not an *energy system model* designed to find an optimal plan to meet an exogenous demand for useful energy.

The design of the model is intended to capture some "stylized facts" about the Swedish electricity and district heating markets. Thus, the model is specifically designed to capture the essentials of an interdependent system of, on one hand, production and use of electricity and, on the other hand, production of and demand for heat. The complex interdependence between the national electricity market and the different regional markets for heating is present both on the supply and the demand side. As mentioned above, production of electricity in combined heat and power plants may require a certain demand for district heating in order to be economical. Furthermore, district heating can be produced by large electric boilers. In addition to that, individual heating systems based on electricity are possible substitutes for district heating. The actual market share of district heating, which is set exogenously, has been determined by the existence of local and regional distribution networks for district heating as well as by the costs associated with the use of other energy carriers in individual heating systems.

From these facts follows that the description of the demand for energy for heating purposes, including different substitution possibilities, is a central part of the model. The foundation of this in the model is the way the country has been divided into different markets for district heating. These regional markets are labeled "Heat Markets".

The first heat market includes areas where large integrated district heating systems exist or are under construction. Thus, "Heat Market 1" is the potential market for large scale (200 MW or more) combined heat and power or combustion plants.

On "Heat Market 2" only small scale district heating plants exist and another special characteristic of "Heat Market 2" is that it consists of areas which are situated where the supply of domestic fuels, such as biomass, is large. In these areas district heating is or will be an alternative way of heating in the future.

"Heat Market 3" consists of the remaining district heating areas in Sweden where no supply of domestic fuels exist. The major difference between this market and "Heat Market 1" is that no large scale district heating plants are assumed to exist on "Heat Market 3".

This separation into different heat markets is made in order to capture the relationship between the alternatives of production and the total demand for heating on a local market for district heating.

For the remaining areas of the country, there exist no district heating today or any plans to construct such plants in the future. In order to complete the picture, a market for light oil and a market for heavy oil are treated alongside with the model. The market for light oil is based on the demand for heat in the housing sector and the market for heavy oil consists mainly of industrial demand. Oil is assumed to be used for combustion in the industry. Both the light and the heavy oil are assumed to be imported at given world market prices. The volumes of the two markets are accounted for in order to capture the total emissions from the Swedish energy sector. The general structure of the model is outlined in Figure 1. The different generation sources and their associated costs are described in Appendix A.

Figure 1 General structure of the model.

The demand for electricity	
- for waterborne heating:	$H = H(P_H , P_F , Y)$
- for direct electric heating:	$V = V(P_V , Y)$
- for all other uses:[2]	$U = U(P_U , P_B , Y)$
The demand for heat on Market 1:	$W_1 = W_1(P_{W1}, Y)$
The demand for heat on Market 2:	$W_2 = W_2(P_{W2}, Y)$
The demand for heat on Market 3:	$W_3 = W_3(P_{W3}, Y)$
The price of light oil (exogenous):	P_F
The price of electricity	
- for waterborne heating:	P_H
- for direct electric heating:	P_V
- for all other uses:	P_U
The price of heavy oil (exogenous):	P_B
The price of heat on Market 1-3:	P_{W1} , P_{W2} and P_{W3}
Real income:	Y

Several of the demand relationships above are of a short-term nature although the model is used in a long-term setting. The short-term nature is partly motivated by the fact that substitution possibilities that exist in the energy sector are often influenced by the political process, and are thus virtually impossible to foresee in the distant future. Given this it seems reasonable to limit the substitution possibilities. Furthermore, an expansion of district heating is very much dependent upon geographical conditions. This together with the political influence on the energy sector motivates that the mixture and growth of the heating systems are exogenously determined in the model. In addition, the fact that future location and size of district heating systems are determined by spatial conditions, such as migration patterns,

[2] This category consists of electricity used in industry, transportation, and in households for non-heating purposes.

which today are hard to predict, makes it difficult to endogenously determine the size of the heating systems.

The numerical values of the different elasticities for the demand equations, as well as other relevant parameter values, are displayed in Appendix B. Since the demand functions in the model are linearisations of nonlinear functions, the elasticities are only exactly right in the area close to the calibrated equilibrium.

Perfect competition is assumed throughout this paper. As was mentioned above the Swedish electricity market has a high degree of concentration which may be important for production levels and market prices. See Andersson and Bergman (1995) for a discussion of competition and prices on the Swedish electricity market.

In energy models it is important to account for the fact that a year is consists of both peak and off-peak periods of electricity demand. In this model time is divided into three different load periods. Furthermore, the production of hydro power is only restricted by the maximum annual energy production and maximum capacity. This implies that hydro power production freely can be redistributed between the different load periods, as long as it does not exceed these limits.[3]

The electricity production is equal to the sum of utilized capacity in different plants times the number of hours they have been in use. For total supply of electricity production to equal demand on the electricity market the following condition has to be met:

$$\begin{aligned}&(1-\sigma_e)\sum_f \sum_a K^{\tau}_{efat}\, T^{\tau} + (1-\sigma_e)\sum_f \sum_a \sum_w K^{\tau}_{cfawt}\, T^{\tau} + (1-\sigma_e)\, IMP^{\tau}_t \\ &= V^{\tau}_t + H^{\tau}_t + U^{\tau}_t + HP^{\tau}_t + EB^{\tau}_t, \qquad \textit{for } \tau = 1,2,3 \textit{ and } t = 1,2,\ldots,9\end{aligned} \tag{1}$$

where σ represents distribution losses, K is utilized capacity and T is number of production hours. Generation can be either from plants producing only electricity, denoted by subscript e, or from plants where electricity is cogenerated with heat, denoted by subscript c. The capacity K_c represents the electrical power capacity in a combined heat and power plant (CHP). The CHPs are located in different heat

[3] In order for this to be correct we have to assume that free hydro power storage capacity exists over the year, which of course is not literally true, but a close enough approximation for our model.

markets, denoted by *w*. The subscripts *f* and *a* refer to different fuels and abatement technologies, respectively. The subscript *t* indicates that the equality has to hold for each time period *t*. The load periods are denoted by superscript τ. *IMP* represents total imports of electricity before losses. Regarding the trade of electricity it is assumed that electricity can be bought at a "world market price". If it is competitive, electricity will be imported and supplied to the national market. There is a restriction on imports due to limited transmission capacity. At all given levels of output the utilization of the different types of plants is determined by cost minimization considerations.

On the demand side, *V* represents the electricity demanded for direct electric heating, *H* is electricity demanded for waterborne heating, and *U* is electricity demanded for other uses, primarily industry. *HP* is electricity demanded for heat pumps and *EB* is electricity demanded for electric boilers. All the demand for electricity is at the user.

For the three heat markets the corresponding market clearing conditions can be written:

$$(1-\sigma_h)\sum_f\sum_a \gamma K^{\tau}_{cfa1t}T^{\tau} + (1-\sigma_h)\sum_f\sum_a K^{\tau}_{hfa1t}T^{\tau} = W1^{\tau}_t, \qquad (2a)$$
$$\text{for } \tau = 1,2,3 \text{ and } t = 1,2,...,9$$

$$(1-\sigma_h)\sum_f\sum_a \gamma K^{\tau}_{cfa2t}T^{\tau} + (1-\sigma_h)\sum_f\sum_a K^{\tau}_{hfa2t}T^{\tau} = W2^{\tau}_t, \qquad (2b)$$
$$\text{for } \tau = 1,2,3 \text{ and } t = 1,2,...,9$$

$$(1-\sigma_h)\sum_f\sum_a \gamma K^{\tau}_{cfa3t}T^{\tau} + (1-\sigma_h)\sum_f\sum_a K^{\tau}_{hfa3t}T^{\tau} = W3^{\tau}_t, \qquad (2c)$$
$$\text{for } \tau = 1,2,3 \text{ and } t = 1,2,...,9$$

where total heat production has to be equal to total demand for each time period *t* and for each load period τ. Plants of cogeneration type, K_c , produce γ units of heat for each unit of electricity. Plants producing only heat are represented by K_h. The *W1*, *W2*, and *W3* represent the demand for heat, at the user, on the different heat markets.

At a given point in time total output is constrained by the installed capacities $\overline{K}_e$, $\overline{K}_c$ and $\overline{K}_h$. For electricity production this can be written:

$\overline{K}_{efa1}$ exogenously given,

$$\overline{K}_{efat} = (1-\delta)\overline{K}_{efat-1} + I_{efat-1}, \qquad for\ t = 2,3,..,9\ and\ \forall\ f\ and\ a \qquad (3)$$

and

$$K^{\tau}_{efat} \leq \alpha_{efa}\overline{K}_{efat} \qquad for\ \tau = 1,2,3,\ \ t = 1,2,..,9\ and\ \forall\ f\ and\ a \qquad (4)$$

where $\overline{K}_{efat}$ is total installed electricity production capacity at time t for each combination of fuel and abatement, respectively. The superscript τ is dropped for *installed* capacity since it is the same over the different load periods during each time period t. The δ is the depreciation rate of the production units. I_{efat} is equal to investments in plants of type *efa* made at time t. From equation (3) it is clear that an investment made at *t-1* will not become available for production until time t. The intention of this is to capture the lag between the investment decision and the availability of the plant associated with investments in large power production units. The condition in equation (4) states that total capacity utilized, K^{τ}_{efat}, have to be less than or equal to the accessibility, α_{efa}, times installed capacity, $\overline{K}_{efat}$, at each time t and load period τ. Corresponding conditions exist for plants of type c and h as well.

The total investment cost is taken in the time period when the investment is made. The issue of remaining terminal values of the installed capacity at the end of the time horizon is important to take into account. This issue is dealt with by decreasing the investment cost over time according to an annuity calculation. Thus, the fact that investments made late in the model's time horizon actually have an economic life beyond the model's time-span is compensated for by a lower investment cost.

There is an equation adding the CO_2 emissions from the different sources of electric power and heat production. This equation can be written as:

$$EMI_t = \sum_{\tau}\sum_{f}\sum_{a}\theta_{efa}K^{\tau}_{efat}T^{\tau} + \sum_{\tau}\sum_{f}\sum_{a}\sum_{w}\theta_{cfa}\left(1+\gamma_{fa}\right)K^{\tau}_{cfawt}T^{\tau} + \sum_{\tau}\sum_{f}\sum_{a}\sum_{w}\theta_{hfa}K^{\tau}_{hfawt}T^{\tau}, \qquad for\ \ t = 1,2,..,9 \qquad (5)$$

where *EMI* is total emissions and θ is the emission coefficient associated with the different types of production, fuels, and abatement technologies.

Total CO_2 emissions can be constrained by an exogenously set limit. In such cases, the relationship can be written as:

$$EMI_t \leq \hat{EMI}_t \qquad for\ t = 1,2,..,9 \qquad (6)$$

where $\hat{EMI}_t$ is the exogenously set limit.

The model is solved by quadratic programming and the objective function that is maximized is the discounted value of the sum of the consumers' and the producers' surpluses of the different time periods. The method of solving is similar to the one used by Manne (1974). The objective function is constructed in such a way that it measures the area under the demand curve, minus the area under the supply curve. Since the demand and supply curves, in each market respectively, contain all information about costs and preferences in the model, so will the objective function. All in all, this process implies that price has to be equal to marginal cost.[4] For the electricity market this can be written:

$$P_{eit} = MC_{eit} \qquad for\ t = 1,2,..,9\ and\ \forall\ i \qquad (7)$$

where P_{eit} is the electricity price in demand category i at time t. MC_{eit} is the marginal cost of electricity production in demand category i at time t. Separate prices are being established in each demand category due to differences in distribution losses to different end users. Another effect of this optimization process is that no investments are made unless the present value is positive.

The model, which in total consists of 42 endogenous variables and 103 equations and inequalities, is run on the GAMS software package. On a Pentium-PC, a standard run takes approximately 35 minutes to solve.

4. The Base Case

Since the purpose of this paper is to estimate impacts of different policies, a natural starting point for further comparisons is a Base case, defined as "business as usual". This implies that nuclear power production is assumed to continue at the current

[4] The marginal cost, MC, can be stated as $MC=VC+\lambda$ where VC is the variable cost and λ is a scarcity rent. The variable costs are described in Appendix A.

levels and no restrictions are enforced on the emissions of CO_2. Regarding capacity expansion it is assumed that no additional hydro or nuclear power is allowed at all, and new capacity from other sources can not be taken into operation until after the turn of the century due to the lead times in the decision and construction process.[5] The exception is biomass which is allowed to expand shortly before the year 2000.[6] The reason for this is the existence of large state funded promotions of renewable energy sources for energy production. However, an upper limit of annual production of 10 TWh has been set for these plants in the model.

The year 1991 has been chosen as the base year for the calibration of the model. The reason being that 1991 was the latest "normal" year in terms of electricity production and to which we have access to data. Thus, the model has been calibrated to the 1991 level of electricity and heat production, both in total and for different types of production categories.[7] This is also the case for the market price of electricity which has been used to calibrate the price level on the different markets described in the previous section.

The time horizon in the model extends from 1991 through the year 2031. For computational reasons it is convenient to employ five-year time intervals where the year referred to is the representative midpoint year, i.e. 1991 is the representative year for the five-year interval 1989-93. Another implication of this is that all years during one five-year period are assumed to be equal, meaning that no specific conclusions can be made regarding, for example, how 1990 differs from 1992.

An ever intriguing issue in Swedish energy policy concerns the way energy taxes are designed. Since the tax level can make the difference whether a plant is competitive or not, it is vital to replicate the tax system as accurately as possible in the design of the model. Since the taxes in Sweden in general, and the energy taxes in particular, are changed every now and then it is difficult to know what they will be in the future. For our dynamic model we have included the latest major revision of the energy tax scheme, which was carried out 1993 - 1994. For the first period the "old" tax regime is used and from period two the "new" system of energy taxes is implemented in the

[5] The exact year is 2004 for new capacity to become available. This year is the first in the period after year 2000 in the model.

[6] Electricity from biomass can be produced by up to 1 TWh/year in 1991 and by 2 TWh/year in 1996.

[7] In order for this to be correct, all costs in the model have to be in 1991 SEK. Since the cost data originally was in 1995 SEK we had to transform them to 1991 SEK. We have assumed that the costs in 1991 were the same as in 1995 in real terms, i.e. the 1995 costs have been adjusted by the inflation in order to obtain the 1991 costs for the model.

model. Even though this tax scheme is likely to change over the years, we use this "new" setting for the remainder of the time horizon in the model since this is our best guess for future energy taxes. One special feature of the energy taxes is that fuels are taxed differently depending on whether they are used for electricity production or other purposes. This fact creates certain modeling difficulties regarding plants that produce a combination of electricity and heat.

A discount rate of 5 % is used throughout the model. This level is chosen mainly for the reason that it is perceived to capture the agents time preference reasonably well, but also for comparative reasons since 5 % appears to be the discount rate that is used in most other studies on this subject.[8] See for example NUTEK (1994).

The driving force of the model is the growth rate of the economy. An annual real growth rate of income of 2 % is assumed over the time horizon of the model. This growth rate is also used in NUTEK (1994) and Nordhaus (1995). The growth of the demand in the different markets is determined by the income elasticities, which are assumed to be 0.7 for all user groups. The exception is direct electric heating which is assumed to have an income elasticity equal to 0.[9]

In Table 6 the estimated levels and growth of the main variables in the base case run are shown. From these estimates it can be seen that electricity prices will rise modestly over time. Since no additions are allowed in nuclear or hydro power production, the increased demand for electricity is at first met through production increases in existing plants that are cost-effective. Additions in electricity production from new biomass plants are made until the exogenous limit of 10 TWh at the user is reached. As demand grows further, new natural gas-fired plants are taken into operation. The use of these plants increase dramatically in this run when the emissions of CO_2 are unrestricted. The implicit CO_2 tax indicates what tax would be needed, in each year respectively, in order to keep the emissions at the prevailing level. Since CO_2 emissions are unrestricted in the Base case, the implicit CO_2 tax is zero for all years. The value of the objective function is normalized to zero since it will be used for comparisons in the subsequent sections. All generation figures in this table and in the following scenarios are at the user.

---

[8] Of course the level of the discount rate can be discussed at length. In order to check for robustness of the results regarding the discount rate we carry out a sensitivity analysis with different levels of the discount rate.

[9] The elasticities chosen are well in line with projections made in the industry when improvements in energy efficiency have been accounted for.

Table 6 Summary of Base case run.

	1991	2000	2010	2020
Electricity price (industry) (1995 SEK/kWh)[10]	0.21	0.26	0.27	0.27
Electricity use (TWh)	132	141	160	188
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	65.2	65.2	65.2
Natural gas	0.0	1.5	13.3	40.7
Fossil fuels	8.1	12.8	12.8	13.1
Biomass	0.1	2.7	10.0	10.0
Imports	0.0	0.0	0.0	0.0
Emissions				
CO_2 (Million tons)	31	42	61	79
Implicit CO_2 tax (1995 SEK/kg CO_2)	0.0	0.0	0.0	0.0
Present value of objective function (Billions of 1995 SEK)	0			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.
Note: Fossil fuels is an aggregate of oil and coal.
Note: Biomass is an aggregate of wooden chips and peat.
Note: Present value of the objective function has been normalized to zero.

5. Different policy scenarios

5.1 Scenario 1 - Phaseout of nuclear power

The first policy scenario concerns the impact of fulfilling the commitment to phase out nuclear power. We do not allow any expansion of hydro power in this scenario, or in any other scenario, since it is our strong belief that expansion of hydroelectric power has almost no political support in Sweden. We do not put any restrictions on the carbon dioxide emissions. There are mainly three reasons for that: First, the wisdom of the commitment not to increase CO_2 emissions above 1990 levels is

[10] 1 SEK = 0.15 US $, 24th of January, 1996.

Table 7 Summary of Scenario 1 - Phaseout of nuclear power.

	1991	2000	2010	2020
Electricity price (industry)				
(1995 SEK/kWh)	0.21	0.32	0.27	0.27
Electricity use (TWh)	132	127	160	188
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	43.5	0.0	0.0
Natural gas	0.0	1.5	78.1	105.6
Fossil fuels	8.1	12.8	12.8	13.1
Biomass	0.1	10.0	10.0	10.0
Imports	0.0	0.0	0.0	0.0
Emissions				
CO_2 (Million tons)	31	52	90	108
Implicit CO_2 tax (1995 SEK/kg CO_2)	0.0	0.0	0.0	0.0
Present value of objective function (Billions of 1995 SEK)	- 117			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.
Note: Fossil fuels is an aggregate of oil and coal.
Note: Biomass is an aggregate of wooden chips and peat.
Note: Present value of the objective function has been normalized to zero in the Base case.

strongly debated. Secondly, the parliament of Sweden has stated that the carbon dioxide target probably will be hard to achieve. And, thirdly, we want to be able to analyze the effects of a nuclear phaseout, “other things being equal“, implying that the only change made in this scenario has to do with the installed nuclear capacity.

This scenario corresponds to the literal date pictured in the referendum, meaning a total phaseout of nuclear power in the year 2010. Since our model has five-year periods and one time period will start by the year 2009, this scenario will impose a total phaseout as of 2009. One third, 3.334 GW, of the existing nuclear capacity will be phased out as of 1999. Another third will be phased out as of 2004 and the last third as of 2009, meaning, as mentioned above, a total phaseout as of 2009. This scenario represents a fairly realistic time schedule if the parliament decides to fulfill the literal date pictured in the referendum. A possible discrepancy between our time schedule and other realistic time schedules that also fulfill the date pictured in the referendum is of no importance to the general conclusions we make, although the specific numbers may differ in each case. In Table 7 the estimated levels and growth of the main variables in Scenario 1 are shown.

The present value of the objective function is in this scenario 117 billion SEK smaller than in the base case. The interpretation of this result is that the cost of a total phaseout, following the time schedule outlined above, is 117 billion SEK for the Swedish society as a whole. The electricity price rises sharply around the year 2000 compared to the base case. The reason is that demand is growing, and when the nuclear power is phased out the drop in electricity production creates a scarcity since not enough capacity can be added at this point in time. This scarcity drives the price to a high level. When new capacity then comes into production the price returns to a lower level. The electricity price then follows the pattern in the base case which is explained by the fact that the same technology is run on the margin in the two cases.

Total generation will be 127 TWh by the year of 2000, 160 TWh by the year of 2010, and 188 TWh by the year of 2020. These figures, when compared to their counterparts in the base case, show that the total generation of electricity is affected by the phaseout around the turn of the century. This is due to the time needed for new capacity to become available. The nuclear power is substituted by natural gas implying a sharp increase in CO_2 emissions over the time-horizon of the model. In fact they rise much faster than they do in the base case, were they rose by 155 % between 1991 and 2020, compared to 248 % during the same time-period in this scenario.

5.2 Scenario 2 - Stabilize CO_2 at the 1990 level

In the second policy scenario the effects of fulfilling the commitment not to increase CO_2 emissions above 1990 levels are studied. Nuclear power is allowed to continue to operate in this scenario in order to analyze the pure effects of implementing the CO_2 commitment.

Our interpretation of the consequences for the energy sector of the commitment not to increase CO_2 emissions above 1990 levels (for the society as a whole) is that the energy sector should not emit more carbon dioxide in any subsequent year than it has in the year of 1990. In brief, the energy sector shall do its share.[11] Consequently we do

[11] The transport sector is the other large emitter of CO_2. Since it is expensive to reduce CO_2 emissions in both the energy sector and the transportation sector one can not motivate that one sector of the two

Table 8 Summary of Scenario 2 - Stabilize CO_2 at the 1990 level.

	1991	2000	2010	2020
Electricity price (industry)				
(1995 SEK/kWh)	0.21	0.29	0.36	0.52
Electricity use (TWh)	132	138	143	147
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	65.2	65.2	65.2
Natural gas	0.0	1.5	3.1	3.1
Fossil fuels	8.1	9.1	3.7	0.0
Biomass	0.1	3.5	10.0	10.0
Imports	0.0	0.0	2.1	9.3
Emissions				
CO_2 (Million tons)	31	31	31	31
Implicit CO_2 tax (1995 SEK/kg CO_2)	0.0	0.09	0.18	0.50
Present value of objective function (Billions of 1995 SEK)	-112			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.
Note: Fossil fuels is an aggregate of oil and coal.
Note: Biomass is an aggregate of wooden chips and peat.
Note: Present value of the objective function has been normalized to zero in the Base case.

not allow the CO_2 emissions in the energy sector described in our model to exceed the 1990 level, which then was equal to 31 million tons of CO_2. In Table 8 the estimated levels and growth of the main variables in Scenario 2 are shown.

As can be seen in Table 8 the present value of the objective function in this scenario is 112 billion SEK smaller than in the base case, which indicates that the cost of fulfilling the CO_2 commitment is smaller than the cost of the nuclear phaseout in Scenario 1.

Electricity prices will rise sharply in the long run and electricity use (or generation) will not increase as fast as in the base case, since the growing demand cannot be met

should carry a smaller share of the load to fulfill the national goal of maintaining CO_2 emissions at the 1990 level.

by other means than price increases due to the CO_2 restrictions. The electricity price in the industry will be 0.29 SEK/kWh by the year of 2000, which is higher than in the base case. But by the years of 2010 and 2020 the price will increase even further, namely to 0.36 and 0.52 SEK/kWh respectively.[12] The reason being that the only way to hold back the growing demand is to raise the prices since no economic viable generation source can be used to meet the increasing demand due to the CO_2 condition. The CO_2 restriction becomes more and more binding over time as the economy grows. This implies that the implicit CO_2 tax has to grow accordingly, in order to keep the prevailing emission level. It can be noted, as a comparison to the implicit CO_2 taxes in the table, that actual CO_2 taxes for manufacturing industries in Sweden were about 0.08 SEK/kg of emitted CO_2 in 1995. Furthermore, it can be seen that the restriction of 10 TWh on biomass production is binding by the year of 2010.

The total generation figures are fairly constant over time, increasing from 132 TWh by the year of 1991 to 147 TWh by 2020. Compared to the base case, where the total generation of electricity rose sharply, this is a very modest development, to say the least. In the year of 2000 the configuration of the sources of generation in this scenario is approximately the same as in the Base case. The configuration of the sources of generation is fairly constant over time in this scenario. The only changes are that fossil fuels partly are substituted by natural gas and that biomass and imports grow.

5.3 Scenario 3 - Phaseout nuclear power and stabilize CO_2 at the 1990 level

The third policy scenario is a combination of Scenario 1 and 2, i.e. the impact of phasing out nuclear power in conjunction with fulfilling the commitment not to increase CO_2 emissions above 1990 levels. This scenario includes three of the four restrictions the Swedish parliament has imposed on the future energy policy discussed in the introduction, namely the restrictions that concern nuclear power, hydro power and CO_2 emissions. The time schedule for the nuclear phaseout and the restrictions on the CO_2 emissions are exactly the same as in Scenario 1 and 2, respectively. In Table 9 the estimated levels and growth of the main variables in Scenario 3 are shown.

Table 9 Summary of Scenario 3 - Phaseout nuclear power and stabilize CO_2 at the 1990 level.

[12] The estimated prices are likely high enough to be perceived as a violation of the stated policy objective, *that electricity should be supplied on internationally competitive terms*.

	1991	2000	2010	2020
Electricity price (industry)				
(1995 SEK/kWh)	0.21	0.34	0.68	0.86
Electricity use (TWh)	132	124	96	94
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	43.5	0.0	0.0
Natural gas	0.0	1.5	17.4	15.9
Fossil fuels	8.1	9.7	0.0	0.0
Biomass	0.1	10.0	10.0	10.0
Imports	0.0	0.0	9.3	9.3
Emissions				
CO_2 (Million tons)	31	31	31	31
Implicit CO_2 tax (1995 SEK/kg CO_2)	0.0	0.16	0.71	1.34
Present value of objective function (Billions of 1995 SEK)	-492			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.
Note: Fossil fuels is an aggregate of oil and coal.
Note: Biomass is an aggregate of wooden chips and peat.
Note: Present value of the objective function has been normalized to zero in the Base case.

It is obvious from Table 9 that the present value of the objective function in this scenario is dramatically lower than in the base case. The cost of a total phaseout, following the time schedule outlined above in conjunction with fulfilling the CO_2 commitment is 492 billion SEK for the Swedish society as a whole. This is more than four times the cost of phasing out nuclear power when no restrictions were imposed on the CO_2 levels.

Electricity prices will rise sharply and electricity use (or generation) will decline severely since the drop in nuclear production cannot be replaced by any other inexpensive source due to the restrictions on the CO_2 emissions. The electricity prices in the industry will be 0.34 SEK/kWh by the year of 2000, 0.68 SEK/kWh by the year of 2010, and 0.86 SEK/kWh by the year of 2020.[13] A considerable increase for every year compared to the Base case.

It can further be noted that the implicit CO_2 tax has to be larger in each year as compared to Scenario 2. The reason being that the CO_2 constraint is even more binding in this scenario due to the nuclear phaseout.

The configuration of the generation sources vary over time. Fossil fuels are substituted by natural gas, nuclear power is gradually phased out, and imports start to take place. In the year of 2000 electricity will mainly be generated by hydro power, nuclear power, fossil fuels, and biomass. In the year of 2010 electricity will mainly be generated by hydro power, natural gas, and biomass. A substantial amount of electricity will also be imported.

In this scenario it is important to point out that the driving force over time is an exogenous income growth in the economy. Since the income growth is exogenous, independent of electricity prices and electricity supply, there is no feedback from the output of the model into the income growth. However, this is not a major flaw when the conditions are fairly normal. Normal in the sense that we have a scenario that we think is at least somehow consistent with the exogenous income growth. It is our strong belief that this is the case in Scenario 1 and 2. But in this scenario, Scenario 3, we get very high prices of electricity and a substantially smaller total generation of electricity. This would probably affect the income growth negatively, and therefore the realism in having the same income growth in Scenario 3 as we have in the previous scenarios could be discussed. However since we want to be able to analyze the pure effects of the restrictions imposed by the parliament we let “other things be equal“, including the income growth.

[13] The estimated prices are definitely high enough to be perceived as a violation of the stated policy objective, *that electricity should be supplied on internationally competitive terms*.

6. Sensitivity analysis

6.1 The value of waiting

In the scenarios above we have followed the decisions already taken concerning Swedish energy policy. Given the assumptions and the model we have used, it has been shown that it obviously is expensive to phase out nuclear power in Sweden, especially if the CO_2 commitment is to be met at the same time. An interesting variation to the scenarios we have studied is to examine what happens if the phaseout is postponed for five or ten years. What we have in mind is a phaseout of nuclear power that follows the same pattern as previously, but with the start-date moved five or ten years into the future.

The results from postponing the phaseout for five years in Scenario 1 show that the saving is equal to 37 billion SEK, measured as the change in the net present value of the objective function. If the nuclear phaseout is postponed another five years the saving turns out to be an additional 24 billion SEK, or 61 billion SEK in total. This implies that the costs of a nuclear phaseout are cut in half if the decision is postponed for 10 years.

Since the really hard-line phaseout case is Scenario 3, where the CO_2 commitment is in effect, it is interesting to examine what the potential savings are from a postponement in this case. If the nuclear phaseout is not started until five years later than according to the original plan, the result is a saving of 76 billion SEK. A postponement of five additional years result in a saving of another 70 billion SEK, or 146 billion SEK in total. From this it is clear that the savings in the CO_2 commitment scenario are lower measured as shares of the total cost, compared to the corresponding savings in Scenario 1, although the savings are much larger in absolute terms.

6.2 Varying some key parameters

Several of the assumptions made in the model might be crucial for the results in the scenarios. We have changed a few key parameters in order to evaluate some of the critical assumptions.

The first assumption concerns the discount rate. The question asked is how sensitive the results are to a 1% change in the discount rate. When a 4 % discount rate is used instead of 5 %, the cost of phasing out nuclear power increases by 18 billion SEK, when no restrictions on the CO_2 emissions are imposed, and by 128 billion SEK, when the restrictions on the CO_2 emissions are in effect. On the other hand, if a 6 % discount rate is used instead of a 5 % discount rate, the cost of phasing out nuclear power decreases by 14 billion SEK, when no restrictions on the CO_2 emissions are imposed. Using the 6 % discount rate decreases the cost of phasing out nuclear power by 97 billion SEK, when the restrictions on the CO_2 emissions are imposed . This indicates that the discount rate is very important to the outcome.

The second assumption that is changed concerns the growth rate of the economy. When the model is run with an annual growth rate of 1% instead of with 2%, the cost of a nuclear phaseout drops by only 2 billion SEK, when no restrictions on the CO_2 emissions are in effect, and by as much as 234 billion SEK when the restrictions on the CO_2 emissions are imposed. Thus, the cost of a nuclear phaseout might be highly dependent upon the growth of the economy.

And finally, the assumption that only 10 TWh of electricity can be produced annually from biomass is changed to 20 TWh. As before the constraint is valid from the year 2000. The result of this is that the cost of phasing out nuclear power, as in Scenario 1, is reduced by 0.3 billion SEK, and the cost of phasing out nuclear power drops by 7 billion SEK, when the restrictions on the CO_2 emissions are imposed. Apparently a doubling of possible electricity production from biomass has no great effect on the costs of a nuclear phaseout.

7. Concluding Remarks

In order to put the costs of a nuclear phaseout into perspective it is interesting to compare the cost with another figure such as the GDP of Sweden. The cost of a phaseout is approximately 7 % of the GDP in 1995, when no restrictions are made on the CO_2 emissions. For the case where the CO_2 emissions are restricted to 1990 levels, the cost of a nuclear phaseout is 30 %, when measured as a share of GDP. Obviously this indicates that the cost of a nuclear phaseout is bound to have a substantial impact on the Swedish economy. It is also interesting to observe that the results in this study are very close to the ones presented by Nordhaus (1995). Especially since our modelling approaches are different.

Although the costs referred to above are substantial one should note that they are based on a frictionless economy, and are thus likely to underestimate the actual costs to society. We know that the economy not is frictionless and that prices and wages do not adapt immediately to changes or shocks.

Another aspect of this is the fiscal effects that will follow a nuclear phaseout. The costs of a nuclear phaseout are likely to significantly increase the Swedish public debt, which may lead to higher costs for borrowing money, especially since the public debt already is large. This in turn may lead to additional costs to society, for example in the form of increased dead-weight losses from the collection of higher taxes. Together this indicates that there are macroeconomic effects that likely will add more to the costs estimated in this study.

All in all this points in the direction that the two goals of phasing out nuclear power and restricting CO_2 emissions are almost mutually exclusive to fulfill. From this follows that the CO_2 emissions are bound to increase above 1990 levels in order to limit the costs of a phaseout. An interesting issue is then how this would affect the international reputation of a country, known for its environmental consciousness, that has committed itself to limit the emissions of CO_2 to a certain level.

References

Amundsen, E. S., J. Björndalen, H. F. Nyhus and S. Tjötta (1994). *A Numerical Model of an Integrated European Electricity Market.* Bergen: SNF Working Paper No. 33/1994.

Andersson, B. and L. Bergman (1995). " Market Structure and the Price of Electricity: An Ex Ante Analysis of the Deregulated Swedish Electricity Market." *The Energy Journal,* Vol. 16, No. 2: 97-109.

Bergman, L., T. Hartman, L. Hjalmarsson and S. Lundgren (1994). *Den Nya Elmarknaden.* Stockholm: SNS Förlag.

Brooke, A., D. Kendrick and A. Meeraus (1988). *GAMS. A User's Guide*. Redwood City Ca.: Scientific Press.

Carlsson, A. (1988) *Estimates of the Costs of Emission Control in the Swedish Energy Sector.* Stockholm: EFI Research Report No. 273.

Fishbone, L.G. and A. Abilock (1981). "MARKAL, A Linear Programming Model for Energy System Analysis: Technical Description of the BNL Version." *International Journal of Energy Research*, Vol. 5: 353-375.

Manne, A. S. (1974) "Waiting for the Breeder", *Review of Economic Studies*, Symposium on the Economics of Exhaustible Resources: 47-65.

Messner, S. (1984), *Users Guide for the Matrix Generator of MESSAGE II, Part I: Model Description and Implementation Guide, Part II: Appendices.* Laxenburg. International Institute for Applied Systems Analysis: WP-84-71a & WP-84-71b.

Nordhaus, W.D. (1995). *The Swedish Dilemma - Nuclear Energy v. the Environment.* Stockholm. SNS Förlag: Occasional Paper No. 74.

Swedish National Board for Industrial and Technical Development (NUTEK), (1991). *Elmarknad i förändring.*

Swedish National Board for Industrial and Technical Development (NUTEK), (1992). *Energirapport 1992.* B1992:9

Swedish National Board for Industrial and Technical Development (NUTEK), (1993). *Energirapport 1993.* B1993:6

Swedish National Board for Industrial and Technical Development (NUTEK), (1994). *Energirapport 1994.* B1994:9

Swedish National Board for Industrial and Technical Development (NUTEK), (1995a). *Energy in Sweden. Facts and Figures.*

Swedish National Board for Industrial and Technical Development (NUTEK), (1995b). *Styrmedel inom energiområdet.*

Swedish National Board for Industrial and Technical Development (NUTEK), (1995c). Technical data about the Swedish electricity production system and parts of the district heating system, through personal contacts with Maria Lundberg and Anders Wikström, NUTEK.

Värmeverksföreningen. *Statistik 1993.* Stockholm.

Appendix A - Production costs

A.1 Variable production costs

Three different categories of electricity production are identified: hydro power, condense power, and combined heat and power. For heat production the main category is ordinary combustion. As for electricity production by condense power there are in turn five different types of plants represented in the model: nuclear, coal, heavy oil (oil 5), light oil (oil 1), and natural gas. The corresponding plants for combined heat and power are: coal, oil 5, chips, peat, and natural gas. Estimates of the variable costs for electricity production associated with the different plants are shown in Table A1.

Table A1 Variable costs in electricity production.

	Fuel costs Öre/kWh[14]	Non-fuel costs Öre/kWh
Condense power		
Nuclear	3.9	3.3
Coal	9.7	1.7 - 7.2
Oil 5	16.2	1.3
Oil 1	33.3	2.6
Natural gas	15.6	2.2
Combined heat and power		
Coal	12.1	1.3 - 7.8
Oil 5	19.7	1.3
Chips	23.7	1.3
Peat	20.4	1.3
Natural gas	18.7	1.3

Note: All costs are at the user in 1995 SEK.
Note: The span in non-fuel costs for coal is due to different abatement technologies.
Note: Total variable costs, i.e. fuel plus non-fuel costs, are referred to as *VC* in Appendix D.

In the model there are no fuel costs or non-fuel costs associated with electricity produced by hydro power. This category of electricity production is only levied with the specific energy taxes that are associated with each category respectively.

[14] 100 öre = 1 SEK

Electricity may also be imported in the model. The cost of this is assumed to be 36 öre/kWh at the user.

Heat produced by ordinary combustion can in the model originate from one of six types of plants: coal, oil 5, chips, peat, waste, and natural gas. The associated variable costs for these heat plants are displayed in Table A2.

Table A2 Variable costs in heat production.

	Fuel costs Öre/kWh	Non-fuel costs Öre/kWh
Ordinary combustion		
Coal	4.7	1.4 - 5.0
Oil 5	7.6	0.7
Chips	9.1	1.5
Peat	7.9	1.5
Waste	8.7	2.9
Natural gas	9.8	0.7

Note: All costs are at the user in 1995 SEK.
Note: The span in non-fuel costs for coal is due to different abatement technologies.
Note: Total variable costs, i.e. fuel plus non-fuel costs, are referred to as *VC* in Appendix D.

A.2 Fixed production costs

Since one important part of the investment decision in the model is associated with the investment cost for different production categories it is vital to include data on this. For the different electricity producing plants the investment costs as well as the fixed annual maintenance costs associated with the plants are shown in Table A3. The corresponding fixed costs for heat production are displayed in Table A4.

Table A3 Fixed costs in electricity production.

	Investment costs SEK/kW	Annual maintenance costs SEK/kW
Condensing power		
Nuclear	15 000	225
Coal	11 500 - 15 500	170 - 230
Oil 5	15 000	220
Oil 1	8 500	125
Natural gas	6 500	95
Combined heat and power		
Coal	16 000 - 19 000	240 - 285
Oil 5	17 000	250
Chips	16 000	240
Peat	16 000	240
Natural gas	7 500	110

Note: All costs are in 1995 SEK.
Note: The span in costs for coal is due to different abatement technologies.
Note: Investment costs are referred to as *IC* in Appendix D.
Note: Annual maintenance costs are referred to as *AMC* in Appendix D.

Table A4 Fixed costs in heat production.

	Investment costs SEK/kW	Annual maintenance costs SEK/kW
Ordinary combustion		
Coal	2 900 - 4 200	45 - 75
Oil 5	2 500	35
Chips	2 900	45
Peat	2 900	45
Waste	5 000	75
Natural gas	1 300	19

Note: All costs are in 1995 SEK.
Note: The span in costs for coal is due to different abatement technologies.
Note: Investment costs are referred to as *IC* in Appendix D.
Note: Annual maintenance costs are referred to as *AMC* in Appendix D.

Appendix B - Parameter values

Real income growth

Δ Y = 2 %

Discount rate

r = 5 %

Table B1 Price and income elasticities.

Own price elasticity	Cross price elasticity	Income elasticity
$\varepsilon_{HH} = -0.3$	$\varepsilon_{HF} = 0.1$	$\varepsilon_Y^H = 0.7$
$\varepsilon_{VV} = -0.3$	-	$\varepsilon_Y^V = 0.0$
$\varepsilon_{UU} = -0.3$	$\varepsilon_{UB} = 0.03$	$\varepsilon_Y^U = 0.7$
$\varepsilon_{W1W1} = -0.3$	-	$\varepsilon_Y^{W1} = 0.7$
$\varepsilon_{W2W2} = -0.3$	-	$\varepsilon_Y^{W2} = 0.7$
$\varepsilon_{W3W3} = -0.3$	-	$\varepsilon_Y^{W3} = 0.7$

Accessibility of installed capacity

Electricity: α_e = 0.80 - 0.94

Heat: α_h = 0.90 - 1.00

Depreciation rate of installed capacity

Net after productivity growth: $\delta = 0$

Table B2 Load periods.

τ	Hours per year	Share of the demand
1	450	0.074
2	1200	0.182
3	7110	0.744

Heat factors in cogeneration plants

Natural gas: $\gamma_n = 1.00$

Other fuels: $\gamma_o = 1.27$

Distribution losses

Electricity: $\sigma_e = 0.07$

Heat: $\sigma_h = 0.09$

Price of imported electricity

Net after losses: P_{IMP} = 36 öre/kWh

Restrictions on imports of electricity

Before losses: $\widehat{IMP}_t$ = 10.0 TWh

Appendix C - Sensitivity analysis

In Table C1 the effects of different scenarios measured as changes in the present value of the objective function are displayed. For each set of scenarios, the present value of the objective function has been normalized to zero in the Base case, i.e. when no nuclear phaseout and no restrictions on CO_2 emissions are enforced. The present value of the objective function is measured in billions of 1995 SEK.

Table C1 Sensitivity analysis.

	No nuclear phaseout	Nuclear phaseout
Key scenarios		
No restrictions on CO_2	0	- 117
CO_2 limited to 1990 levels	- 112	- 492
Phaseout postponed 5 years		
No restrictions on CO_2	0	- 80
CO_2 limited to 1990 levels	- 112	- 416
Phaseout postponed 10 years		
No restrictions on CO_2	0	- 56
CO_2 limited to 1990 levels	- 112	- 346
Discount rate 4 %		
No restrictions on CO_2	0	- 135
CO_2 limited to 1990 levels	- 147	- 620
Discount rate 6 %		
No restrictions on CO_2	0	- 103
CO_2 limited to 1990 levels	- 85	- 395
Economic growth 1 %		
No restrictions on CO_2	0	- 115
CO_2 limited to 1990 levels	- 21	- 258
10 TWh new biomass[15]		
No restrictions on CO_2	0	- 117
CO_2 limited to 1990 levels	- 109	- 484

[15] Defined as a possibility to expand production with an additional 10 TWh as from the year 2000.

Appendix D - Model specification[16]

The objective function[17]

$$OBJ = \sum_{t=1}^{9} \frac{5}{(1+r)^{5(t-1)}} \left\{ \int_0^{V_t^*} P_V(V_t)\,dV_t + \int_0^{H_t^*} P_H(H_t)\,dH_t + \int_0^{U_t^*} P_U(U_t)\,dU_t + \int_0^{HP_t^*} P_{HP}(HP_t)\,dHP_t \right.$$

$$+ \int_0^{EB_t^*} P_{EB}(EB_t)\,dEB_t + \int_0^{B_t^*} P_B(B_t)\,dB_t + \int_0^{F_t^*} P_F(F_t)\,dF_t$$

$$-(1-\sigma_e)\sum_{\tau}\sum_{f}\sum_{a} VC_{efat} K_{efat}^{\tau} T^{\tau} - (1-\sigma_e)\sum_{\tau}\sum_{f}\sum_{a} VC_{cfat} K_{cfat}^{\tau} T^{\tau}$$

$$-(1-\sigma_h)\sum_{\tau}\sum_{f}\sum_{a}\sum_{w} VC_{hfawt} K_{hfawt}^{\tau} T^{\tau}$$

$$-(1-\sigma_h)\sum_{\tau}\sum_{w} VC_{EBt} K_{EBwt}^{\tau} T^{\tau} - (1-\sigma_h)\sum_{\tau}\sum_{w} VC_{HPt} K_{HPwt}^{\tau} T^{\tau}$$

$$-\sum_{f}\sum_{a} AMC_{efat}\overline{K}_{efat} - \sum_{f}\sum_{a} AMC_{cfat}\overline{K}_{cfat} - \sum_{f}\sum_{a}\sum_{w} AMC_{hfawt}\overline{K}_{hfawt}$$

$$-\sum_{w} AMC_{EBt}\overline{K}_{EBwt} - \sum_{w} AMC_{HPt}\overline{K}_{HPwt} - 0.2\sum_{f}\sum_{a} IC_{efat} I_{efat}$$

$$-0.2\sum_{f}\sum_{a} IC_{cfat} I_{cfat} - 0.2\sum_{f}\sum_{a}\sum_{w} IC_{hfawt} I_{hfawt} - 0.2\sum_{w} IC_{EBt} I_{EBwt}$$

$$\left. -0.2\sum_{w} IC_{HPt} I_{HPwt} - P_{Bt} B_t - P_{Ft} F_t - P_{IMPt}(1-\sigma_e)\left(IMP_t^1 + IMP_t^2 + IMP_t^3\right) - TAX_t \right\}$$

[16] Besides the restrictions stated in this appendix, there are some additional generation and capacity restrictions which are not of general importance and therefore not stated here.

[17] The market clearing quantities of the variables in question are denoted by star. The variable TAX represents total taxes collected in the energy sector. It is important to point out that the changes in the present value of the objective function displayed in the scenarios above, have been calculated by using the objective function OBJ, taking into account that total taxes collected in the energy sector vary between different scenarios.

Subject to:

Market clearing condition - Electricity market

$$(1-\sigma_e)\sum_f\sum_a K_{efat}^{\tau} T^{\tau} + (1-\sigma_e)\sum_f\sum_a\sum_w K_{cfawt}^{\tau} T^{\tau} + (1-\sigma_e) IMP_t^{\tau}$$

$$= V_t^{\tau} + H_t^{\tau} + U_t^{\tau} + HP_t^{\tau} + EB_t^{\tau}, \qquad for\ \tau = 1,2,3\ and\ t = 1,2,...,9$$

Market clearing conditions - Heat markets

$$(1-\sigma_h)\sum_f\sum_a \gamma K_{cfa1t}^{\tau} T^{\tau} + (1-\sigma_h)\sum_f\sum_a K_{hfa1t}^{\tau} T^{\tau} = W1_t^{\tau}, \qquad for\ \tau = 1,2,3\ and\ t = 1,2,...,9$$

$$(1-\sigma_h)\sum_f\sum_a \gamma K_{cfa2t}^{\tau} T^{\tau} + (1-\sigma_h)\sum_f\sum_a K_{hfa2t}^{\tau} T^{\tau} = W2_t^{\tau}, \qquad for\ \tau = 1,2,3\ and\ t = 1,2,...,9$$

$$(1-\sigma_h)\sum_f\sum_a \gamma K_{cfa3t}^{\tau} T^{\tau} + (1-\sigma_h)\sum_f\sum_a K_{hfa3t}^{\tau} T^{\tau} = W3_t^{\tau}, \qquad for\ \tau = 1,2,3\ and\ t = 1,2,...,9$$

Capacity conditions - Electricity production

$\overline{K}_{efa1}$ exogenously given,

$$\overline{K}_{efat} = (1-\delta)\overline{K}_{efat-1} + I_{efat-1}, \qquad for\ t = 2,3,...,9\ and\ \forall\ f\ and\ a$$

$$K_{efat}^{\tau} \le \alpha_{efa}\overline{K}_{efat} \qquad for\ \tau = 1,2,3,\ t = 1,2,...,9\ and\ \forall\ f\ and\ a$$

Emission constraints

$$EMI_t = \sum_{\tau}\sum_f\sum_a \theta_{efa} K_{efat}^{\tau} T^{\tau} + \sum_{\tau}\sum_f\sum_a\sum_w \theta_{cfa}\left(1+\gamma_{fa}\right) K_{cfawt}^{\tau} T^{\tau} + \sum_{\tau}\sum_f\sum_a\sum_w \theta_{hfa} K_{hfawt}^{\tau} T^{\tau},$$

$$for\ t = 1,2,...,9$$

$$EMI_t \le \hat{EMI}_t \qquad \textit{for } t = 1, 2, \ldots, 9$$

$\hat{EMI}_t$ exogenously given

Import constraints

$$IMP_t^1 + IMP_t^2 + IMP_t^3 \le \hat{IMP}_t \qquad \textit{for } t = 1, 2, \ldots, 9$$

$\hat{IMP}_t$ exogenously given