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Finn Roar Aune, Torstein Bye,
Tor Arnt Johnsen and Alexandra Katz

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A General Equilibrium Model of the Nordic Countries Featuring a Detailed Electricity Block

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Abstract:
This paper presents a Nordic energy market model, NORMEN, which links together the electricity market, the economy and the environment in a general equilibrium framework. The model is an extension of an earlier partial energy market model developed at Statistics Norway. In contrast to that and other partial models (i.e. the bulk of the literature) where there are no feedback effects from the electricity prices to the rest of the economy, in NORMEN all prices are determined simultaneously. By adding a macroeconomic block to the model, the scale effects on electricity demand due to electricity price changes can be captured, rather than just first round price effects. In this paper, we document the model structure of NORMEN, parameter estimation procedures, and data collecting process. This document marks the end of the first stage of this project: model building and data collecting. In the next stage, we will use the model, among other things, to analyze the effect of various energy policies on electricity consumption, electricity prices, CO2 emissions, and several general economic indicators.

Keywords: Electricity demand, computable general equilibrium models, energy policy analysis

JEL classification: E10, F47, Q43

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Address: Finn Roar Aune, Statistics Norway, Research Department,
P.O.Box 8131 Dep., N-0033 Oslo, Norway. E-mail: fau@sssb.no

Torstein Bye, Statistics Norway, Research Department, E-mail: tab@ssb.no

Tor Arnt Johnsen, Statistics Norway, Research Department, E-mail: taj@ssb.no

Alexandra Katz, Statistics Norway, Research Department, E-mail: aka@ssb.no

1. Introduction

Over the last few years, electricity industries the world over have come under increasing pressure to deregulate. This is partly due to the realization that vertically integrated electricity monopolies have been inefficient and that welfare gains could be realized by opening up electricity systems to competition. Furthermore, several countries have already begun the liberalization process with relative success. The UK in 1990 was the first European country to begin liberalizing its electricity supply industry (ESI) and Norway the second a year later. Because Sweden has recently followed suit and Finland is not long behind, a common deregulated Nordic electricity market is now almost a reality. Together, Norway, Sweden, and Finland account for about 90% of Nordic power generation, so even though Denmark will probably not deregulate for some time, the Nordic electricity market can still be basically characterized as open. Since there are large variations across countries in power generation methods and thus in cost structures, there may be substantial returns to Nordic trade in electricity.

A partial energy market model for the Nordic countries was developed a few years ago at Statistics Norway in order to analyze the supply and demand for energy in four countries: Norway, Sweden, Denmark, and Finland. The Nordic energy market model considered the final demand and supply for fuel oil and electricity using water, gas, oil, coal, uranium, and biofuels as inputs in electricity production. It was used to analyze the effects of establishing a Nordic energy market and to test the response of energy demand to various scenarios of CO_2 taxes, see Bye et al. (1995), Bye and Johnsen (1995), and Aune et al. (1995). However, the model relied on exogenous economic activity levels and prices.

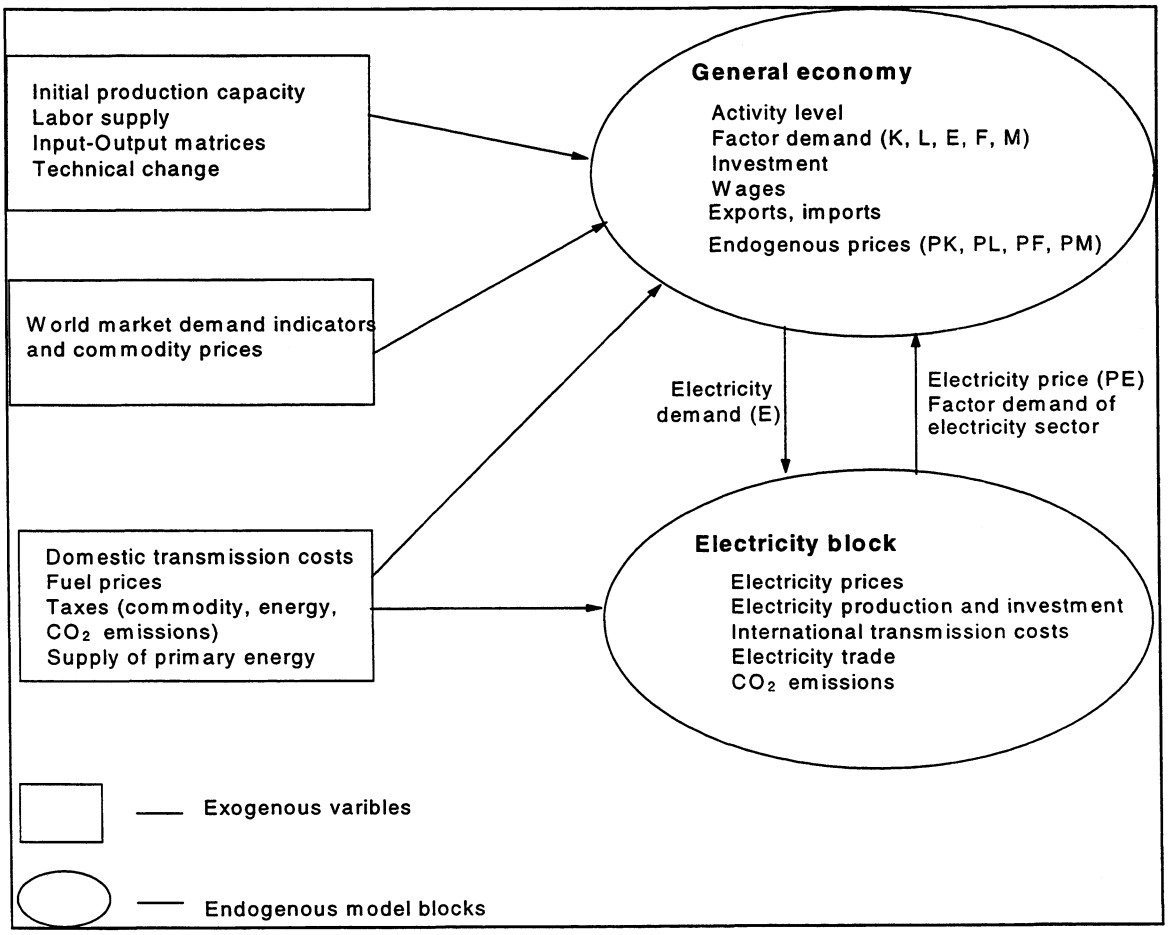
A new and extended version of the Nordic energy market model is presented in this paper. The model is innovative in that it is a general equilibrium model featuring a detailed electricity block, combined with trade of electricity between countries. As figure 1.1 shows, the new general economy blocks determine the activity levels of the Nordic economies (GDP) and are linked to the (old) electricity block of the model. Whereas before there were no feedback effects from the electricity prices to the general economy, in NORMEN[1] all domestic prices (of electricity and other goods) are determined simultaneously. Such a linkage is important because electricity prices differ widely among countries as well as for various domestic end-uses. By using a model where the electricity market and general economy are connected, scale effects on electricity demand due to electricity price changes can be captured, rather than just first round price effects. Such price changes might result, for example, from

[1] NORdic Macro ENergy market model

the introduction of less expensive generation methods, carbon taxation, or a change in trade conditions. Furthermore, the model captures the effects of structural changes in the general economy which result from (non-electricity) relative price changes.

The structure of the paper is as follows. Section 2 presents the macroeconomic block of the model, while section 3 reviews the electricity market block. Section 4 describes the data collection process and includes a detailed list of all data sources. Finally, section 5 presents a reference scenario of the model along with results from implementing higher CO_2 taxes and/or that every Swedish nuclear reactor is phased out after 25 years' use (as opposed to 40, which is assumed to be the profitable lifetime of a plant in the reference scenario). The economies are each divided into six sectors: metal, pulp & paper, other manufacturing, services, other, and electricity.[2] The model is calibrated to the year 1991 and is simulated until the year 2030.

Figure 1.1 The Structure of NORMEN



[2] Since Denmark has a negligible pulp and paper industry, it is replaced by the chemicals plus food, beverage and tobacco manufactures. The 'other' sector for Norway is oil/foreign shipping (excluding refineries), while for Sweden and Finland it is chemicals. No 'other' sector is used for Denmark.

2. The Macroeconomic Block

2.1. Production and Factor Demand Equations

Production in sector *j*, (X_j), is defined as a Cobb-Douglas function of the five inputs (x_n), where n = electricity (E), fuel oil (F), capital (K), labor (L), and other material inputs (M) for each Nordic country.[3]

(1) $$X_j = A_j \prod_n x_{nj}^{\alpha_{nj}}, \qquad n = E, F, K, L, M; \ \forall j \neq 6$$

where α_{nj} and A_j are coefficients and $\alpha_{nj}>0$. The assumption of constant returns to scale implies

(2) $$\sum_n \alpha_{nj} = 1. \qquad n = E, F, K, L, M; \ \forall j \neq 6$$

Assuming cost minimizing behavior, deriving the first order conditions and combining them with the primal function yields the dual cost function, see Varian (1978),

(3) $$C(\mathbf{p}, X_j) = A_j^{-1}(\prod_n \alpha_{nj}^{\alpha_{nj}})^{-1}(\prod_n P_{nj}^{\alpha_{nj}})X_j,$$

where **p** is the vector of input prices. Applying Shephard's lemma (i.e. taking the first order derivatives of the cost function with respect to input price) yields the conditional factor demand function[4], and thus the unit input demand coefficient for factor *n* in sector *j* can be expressed as

(4) $$Z_{nj} = a_j \alpha_{nj} P_{nj}^{-1} \prod_n P_{nj}^{\alpha_{nj}}, \qquad n = E, F, K, L, M; \ \forall j \neq 6$$

where

(5) $$a_j = (A_j \prod_n \alpha_{nj}^{\alpha_{nj}})^{-1}.$$

The coefficient A_j then calibrates the model.

[3] The country index is omitted for ease of presentation. Electricity (sector *j=6*) is treated separately in Section 3.

[4] When calibrating the input demand functions, there is an exact identity between the coefficients in these functions and the primal function.

2.2. Consumption

Private consumption (C) is a function of national income (Y), according to

(6) $$C = \beta_0 + \beta_1 Y,$$

where β_0 and β_1 are coefficients. Let P_i represent the purchaser price of good *i* (constructed to be analogous to the consumption sectors), such that

(7) $$P_i = [MB_i PW_i + (1 - MB_i)PX_i](1 + TC_i),$$

where MB_i is the commodity specific import share, PW_i is the world market price of commodity *i*, PX_i is the domestic producer price of the good and TC_i reflects the excise tax rate on good *i* plus the non-refundable VAT rate on good *i* delivered to private consumption. Then, maximization of the assumed utility function

(8) $$W = \sum_i \kappa_i \ln(C_i - \gamma_i),$$

subject to the budget constraint

(9) $$C = \sum_i P_i C_i$$

implies standard LES (linear expenditure system) consumption demand functions for all goods except electricity,

(10) $$C_i = \varphi_i + \frac{\kappa_i (C - m)}{P_i} + CE_i, \qquad \forall\, i \neq 6$$

where κ_i represents the marginal budget share of good *i*, ϕ_i reflects the total minimum consumption of good *i*, and CE_i is an exogenous calibration variable.[5] The aggregate minimum consumption expenditure, *m*, (in current prices) is defined as

[5] See, for instance, Aasness and Holtsmark (1993) for a detailed description of consumer demand.

(11) $$m = \sum_i P_i \phi_i \, .$$

The marginal budget share estimates used are reported in table 2.1. For Norway, the 1991 (base year) shares are derived from estimates from Aasness and Holtsmark (1993). For Sweden, they come from the National Institute of Economic Research (1996) and are based on the average of the period 1970-1992 (1985 base year). The Danish shares are based on the 1990 consumption parameters estimated for their GESMEC model.[6] Unfortunately, no recent marginal budget shares for Finland have been found, and therefore they are temporarily 'guesstimated' by the Norwegian ones.

Table 2.1 Consumption parameter estimates[a]

Sector	Norwegian marginal budget shares, 1991	Swedish marginal budget shares, avg. 1970-1992	Danish marginal budget shares, 1990	Finnish marginal budget shares, 1991*
Metal			.06[b]	
P & P			.06[c]	
Other Industries	.281	.340	.14	.281
Services	.719	.660	.73	.719
Other				
Electricity				

[a] Note that since metal, pulp and paper, chemicals and oil/ocean transport (in 'Other') are not consumer goods, they are not relevant here. Electricity consumption is determined in the electricity block.
[b] NB electricity-intensive industries
[c] NB food products
Sources: Norway: Aasness and Holtsmark (1993); Sweden: National Institute of Economic Research (1996); Denmark: derived from Danish Economic Council (1995a); *Finland: temporarily 'guesstimated' by Norwegian shares.

2.3. Investment

Capital input is determined by the production functions and gross investment by equation (12). That is, we assume that gross investment, J_j, has full capacity effect the same period that investment takes place,

(12) $$J_{jt} = K_{jt} + D_{jt} - K_{j(t-1)},$$

where D_j is depreciation calculated according to

[6] See Danish Economic Council (1995a).

(13) $$D_{jt} = \delta_j K_{j(t-1)},$$

and where the depreciation rate, δ_j, is determined in the base year. The electricity generating sector is treated in a bit more detail. Summing over the *K* different electricity production technologies yields total new investment in that sector

(14) $$J_{jt} = \sum_k J_{kjt} . \qquad j = 6 \text{ (el.)}; k = 1, 2, \ldots K$$

The *K* possible technologies are: condensing generation (coal fired), coal dust, coal-gas, coal-fired fluid bed, condensing generation (oil-fired), back pressure, gas turbine (new), combined cycle (gas) based on either national sources[7] or Norwegian tradable Troll gas/tradable Halten gas, wood-fired steam injected gas cycle (STIG), condensing generation (peat-fired), condensing generation (biofuel-fired), and new hydropower (only for Norway, and consisting of four different types according to development costs).

2.4. Foreign Trade

In accordance with the Armington hypothesis, which states that domestic and foreign goods are imperfect substitutes, exports of commodity *i* (XP_i) for each country depend on the domestic purchaser price (PX_i) relative to the world market price of the good (PW_i) and on the world market demand indicator for the commodity (MI_i). Accordingly, exports to the rest of the world are represented as

(15) $$XP_i = \lambda_0 \left(\frac{PX_i}{PW_i}\right)^{\varepsilon_{pi}} MI^{\varepsilon_{mi}}, \qquad i \neq 6$$

where ε_{pi} and ε_{mi} are the relative price and market elasticities, respectively, and λ_0 is a calibration parameter. Table 2.2 presents the export elasticities implemented in the model.

[7] A national source is an exogenously limited supply of natural gas which is allocated to just one country. (Russian gas to Finland. Danish gas to Denmark and Sweden.)

Table 2.2 Estimated export demand elasticities

	NOR	NOR	SWE	SWE	DEN	DEN	FIN[a]	FIN[a]
Sector	ε_{pi}	ε_{mi}	ε_{pi}	ε_{mi}	ε_{pi}	ε_{mi}	ε_{pi}	ε_{mi}
Metal	-1.84	1	-5.0	1	-1.8[d]	1	-5.0	1
P & P	-1.62	1	-5.0	1	-1.2[e]	1	-5.0	1
Other Indust.	-2.51	1.39	-1.89	1	-1.8	1	-1.89	1
Services	-1.11	.083	-1.66	1	-1.43	1	-1.66	1
Other			-1.53[c]	1			-1.53[c]	1
Elec.			-5.00[b]	1			-5.00[b]	1

[a] Note that since no estimates were located for Finland, they are approximated by the Swedish ones.
[b] NB includes gas
[c] NB chemicals
[d] NB electricity intensive industries
[e] NB food products
Sources: Lindquist (1993) for Norway, National Institute of Economic Research (1996) for Sweden, and derived from Danish Economic Council (1994) for Denmark.

Analogously, imports of good *i* (MP_i) equal a share (MB_i) of domestic demand, see Section 2.5. This import share of good *i* depends on the price ratio between the domestically produced and imported good, on the domestic supply of the good, and on the degree of substitutability between domestic and foreign varieties

$$(16) \qquad MB_i = \chi_0\left(\frac{PX_i}{PW_i}\right)^{\varepsilon_{si}} + CP_i, \qquad i \neq 6$$

where CP_i is a calibration parameter for good *i*. The import elasticity estimates used in the model are reported in table 2.3.

Table 2.3 Estimated import elasticities

	NOR	SWE	DEN	FIN[a]
Sector	ε_{si}	ε_{si}	ε_{si}	ε_{si}
Metal	.81	1.1	1.2[d]	0.8
P & P	2.35	1.1	.9[e]	2.3
Other Industries	2.51	.8	1.2	1.3
Services	1.11	1.01	1.43	1.2
Other	-	0.8[c]		1.0[c]
Electricity	-	0[b]	-	0[b]

[a] Note that since no estimates were located for Finland, they are 'guestimated' by a combination of the Swedish and Norwegian ones.
[b] NB includes gas
[c] NB chemicals
[d] NB electricity intensive industries
[e] NB food products
Sources: Naug (1994) for Norway, National Institute of Economic Research (1996) for Sweden, and Danish Economic Council (1994) for Denmark.

2.5. Commodity Market Equilibrium

Imports of good *i* equal a share (MB_i) of domestic demand for each good. Total supply of commodity *i* in each country must equal total domestic usage of the good plus exports and a correction term, Ω_{i0} (determined in the base year). Note that the model has a single product production structure, such that *i=j* and that electricity and fuels are treated in detail in Section 3.

$$MP_i = MB_i[\sum_j \xi_{ij}M_j + \sum_j \eta_{ij}J_j + C_i + G_i + DL_i] \qquad \forall i \neq 6$$

$$(17) \quad X_i = (1-MB_i)[\sum_j \xi_{ij}M_j + \sum_j \eta_{ij}J_j + C_i + G_i + DL_i] + XP_i + \Omega_{i0} \qquad \forall i \neq 6$$

$$X_i^E + MP^E = \sum_j E_j + G_i + XP^E \qquad i = 6(\text{el.}); \forall j$$

$$X_i^F + MP^F = \sum_j F_j + G_i + XP^F \qquad i = 6(\text{fuel.}); \forall j$$

That is, output of good *i* (basic value) equals the sum of deliveries of good *i* to intermediate production, to investment, to private consumption C_i (basic value), to public consumption G_i (basic value), to changes in stocks (basic value) DL_i, and to exports XP_i, plus the correction term. The coefficients ξ_{ij}, and η_{ij} from the input-output matrices convert purchasers' values (M_j and J_j) to basic values. They are calculated, respectively, as

ξ_{ij} = deliveries of good *i* to intermediate inputs in sector *j* (basic value) divided by the total value of intermediate inputs to sector *j* (net (refundable VAT) purchaser prices in the base year)

η_{ij} = the ratio of deliveries of good *i* (basic value) for investment to the total value of investment in sector *j* (purchaser prices in the base year)

2.6. Prices

In the long run, domestic producer prices must equal total unit cost, i.e. there are no incentives for any firms to enter or exit the market. Total unit cost in sector *j* is defined by

(18) $$PX_j = \sum_n Pn_j Zn_j + (\frac{TM_j}{X_j}), \qquad n = E, F, K, L, M; \forall j$$

where TM_j is net sectoral taxes in production sector *j*. The purchaser price (net refundable VAT) for intermediate inputs other than electricity and fuel in sector *j* is determined according to

(19) $$PM_j = \sum_i (1+T_{ij})\xi_{ij}[MB_i PW_i + (1-MB_i)PX_i],$$

where T_{ij} is a composite tax rate which accounts for the taxes on deliveries of good *i* to sector *j* (i.e. it includes the rate of non-refundable VAT and the rate of excise tax on good *i* delivered to intermediate inputs in sector *j*).

The domestic purchaser price (end-use price) of electricity in a sector (PE_j)[8] depends on the c.i.f. import price of electricity (PE^{cif}), the margin which covers transmission and distribution costs (MG_j^E), the net tax on electricity used by sector *j* (TE_j), and the value added tax rate on electricity usage (VAT_j).

(20) $$PE_j = (PE^{cif} + MG_j^E + TE_j)(1 + VAT_j).$$

[8] A detailed description of energy price determination is presented in Bye et al. (1995).

Similarly, the end-use domestic purchaser price of fuels (PF_j) is a function of the raw oil c.i.f. import price (or plant price) (PF^{cif}), the refining and distribution margin (MG_j^F), a fuel tax imposed on sector j (TV_j^F), a CO_2 tax ($TCO2_j$), and the value added tax rate

(21) $$PF_j = (PF^{cif} + MG_j^F + TV_j^F + TCO2_j)(1 + VAT_j).$$

Relative differences in wage costs are assumed to be fixed, such that the yearly wage clears the market. The wage (to the employer) is calculated as

(22) $$PLX_j = PL_j(1 + TLX_j),$$

where TLX_j is the rate of employer contributions and PL_j is the (net of employer tax) wage received by the worker. The user cost of capital is determined as

(23) $$PK_j = (\rho_j + \tilde{\rho}_j + \delta_j)\sum_i \eta_{ij}[MB_i PW_i + (1 - MB_i)PX_i],$$

where ρ_j is the rate of return on real capital in sector j and the depreciation rate, δ_j, is calibrated for each sector. The parameter $\tilde{\rho}_j$ represents the divergence of ρ_j from its long run value (i.e. it equals zero in the long run). This specification is used to prevent negative gross investment levels in the model, since the base year calibration may reflect over-capacity in the short run.

2.7. Income generation

The operating surplus in all private production sectors except electricity, (OS_j), is defined as factor income minus total wage costs

(24) $$OS_j = PX_j X_j - PM_j M_j - PE_j E_j - PF_j F_j - PLX_j L_j - D_j PI - TM_j - T_j M_j \qquad j \neq 6(\text{el.})$$

where PI is a deflator for total investment.

The private sector receives this operating surplus and wages, reduced by their respective tax rates, TL_j and TOS_j, plus the total producer surplus (i.e. profit) from the electricity sector (POV), after tax

(25) $$Y_P = \sum_{j\neq 5}[OS_j(1-TOS_j) + PL_jL_j(1-TL_j)] + POV(1-TPOV),$$

where POV is defined as the market value of electricity sales minus the area under the long-run marginal cost curve (C(u))

(26) $$POV = \sum_{k}[(PE)SE_k - \int_0^{SE_k} C(u)du]'$$

and where SE_k is the total domestic quantity of electricity supplied using technology *k*.

The income received by the government (Y_G), thus equals the sum of income taxes, operating surplus taxes, commodity taxes (including taxes on electricity and fuel oil in the traditional production sectors), production taxes, taxes on fuel use in the electricity generation sector, consumption taxes, and value added taxes on oil and electricity which are paid by households

(27) $$\begin{aligned} Y_G = &\sum_j PL_jL_j(TL_j + TLX_j) + \sum_{j\neq 5}(OS_jTOS_j) + POV(TPOV) + + \sum_i\sum_j T_{ij}M_j \\ &+ \sum_j TM_j + \sum_m\sum_k t_{mk}U_{mk} + \sum_{i\neq 5} TC_iC_i + \sum_j (TV_j^FF_j + TCO2_j^FF_j + TE_jE_j) \\ &+ \sum_j \{[(PF_j^{cif} + MG_j^F + TV_j^F + TCO2_j)F_j + (PE_j^{cif} + MG_j^E + TE_j)E_j]VAT\} \end{aligned}$$

where t_{mk} and U_{mk} are, respectively, the tax rate for and use of energy good *m*, using electricity production technology *k* (*m* includes electricity, oil, gas, coal, etc.).

2.8. The Trade Balance

The trade balance (*H*) for each country depends on net exports of the 5 commodities plus net energy exports (see Section 3)

(28) $$H = \sum_{i\neq 6}(XP_i - MP_i) + \sum_m (XP_m^E - MP_m^E)$$

3. Electricity Market Block

3.1. Electricity Supply

Short run

At the starting point of the model, energy production capacity is larger than demand in the various countries. All of the Nordic countries have had regulated energy markets. Expansion is undertaken to ensure that demand can be met, plus a security margin. Some of the existing capacity is first put into use when demand increases. Due to the long lifetime of the existing capacity, it can take a long time for the new capacity to expand. Therefore, both short and long run cost functions are specified in the model. By short run, it is meant the time horizon until the expansion of new capacity becomes profitable.

In the short run, the maximum energy production capacity is given. Capacity data (KAP_k) are calculated for the model's first year (1991) for all of the electricity production technologies (*k*) which are specified, see Section 2.3. Available energy production capacity in a country equals the sum over all of the capacities for the *K* different technologies

(29) $$KAP = \sum_k KAP_k . \qquad k = 1, .., K$$

The short run supply of electricity is ranked according to rising variable costs. The fuel efficiency of technology *k*, V_k, reflects the relation between the amount of energy in the form of electricity which is produced by the supplied fuel and the theoretical energy content as a whole. For example, an energy unit of coal supplied to a conventional coal-using plant yields .35 energy units of electricity. The rest of the energy is lost in the combustion process in the form of heat. The variable cost (CV_k) for an energy production technology is constant when the price of supplied energy, P_k, is given

(30) $$CV_k = (\Phi_k + \frac{P_k}{V_k}), \qquad k = 1, .., K$$

where Φ_k represents the part of operating costs (in excess of energy costs) which depend upon production. Since we do not have data for this, the operating costs are included in the fixed costs and are assumed to be independent of production for as long as the plant operates.

Long run
If the market price of electricity at a power plant exceeds the long run marginal cost, defined as the sum of fixed and variable costs of new operations (calculated per kWh per year), then there will be investment in new capacity.

It is assumed that no electricity producer has enough power to influence the market, and thus that there can be no monopolies in electricity trading. It is also assumed that the capacity of a power plant can grow continuously. Since every individual plant is small relative to the total market, and since there is also significant flexibility with regard to the scale of heating power plants, this is a reasonable assumption.

The available heating technology is comprised partly of internationally proven technologies like oil or coal-fired condensing generation and gas-fired combined cycle power, and partly of more country-specific technologies like peat-fired (condense) plants in Finland, industrial combined heat and power (CHP) in Finland and Sweden, and straw-fired CHP in Denmark. A new type of gas fired technology (fuel cell) is also currently under development in Denmark. These types of processes have future potential due to their high fuel efficiencies, but for now the costs are too high for such technologies to be commercially profitable.

Data on fixed unit costs for new electricity technologies are shown below in table 3.1. Starting with investment costs for effective capacity (per MW), data on the total hours of plant operation per year, a discount rate of 7% and a given capital lifetime, fixed capital costs per kWh, or the user price of energy capital, can be calculated. In addition to fixed capital costs, there are also operating costs which depend on production. These are included in the Table 4 data. In order that the costs are comparable, each established plant is assumed to operate 5100 hours per year. This corresponds to about the average use time for the sum of industrial and ordinary consumption.

Table 3.1 Fixed unit costs, new main power stations, 1991 NOK/kWh

Technology	Fuel	NOR	SWE	DEN	FIN
Condense	Coal	-	.252	-	.252
Coal dust	Coal	-	.170	.170	-
Coal gas	Coal	-	-	.210	-
Fluid bed	Coal	-	.210	.210	-
Condense	Oil	-	.150	-	.150
Gas turbine	Oil	-	.108	-	-
Combined cycle	Gas	12.3	.123	.123	.123
BIG/STIG	Biofuels	-	.186	-	1.19
Condense	Peat	-	.178	-	.178
Condense	Biofuels	-	.216	-	.216

Source: Norwegian Water and Energy Board (1994) and Bye et al (1995).

Variations in competence levels, national priorities, quality requirements and standards, and wage levels, can result in significant differences in investment costs among the different Nordic countries. However, we ignore these differences, and instead use the same costs for the same technology in different countries. Fuel efficiency (V_k), that is, the plant's ability to convert the energy supplied into electric energy, is reported in table 3.2 for the various energy technologies.

Table 3.2 Fuel efficiency in new power plants[a]

Technology	Fuel	NOR	SWE	DEN	FIN
Condense	Coal	-	0.39	-	0.39
Coal dust	Coal	-	0.45	0.45	-
Coal gas	Coal	-	-	0.42	-
Fluid bed	Coal	-	0.37	0.37	-
Condense	Oil	-	0.36	-	0.36
Gas turbine	Oil	-	0.32	-	-
Combined cycle	Gas	0.58	0.58	0.58	0.58
BIG/STIG	Biofuels	-	0.44	-	0.44
Condense	Peat	-	0.39	-	0.39
Condense	Biofuels	-	0.34	-	0.34

[a] Note that most of these fuel efficiencies are based on current technology. However, new technology will likely raise these efficiencies significantly. The model user can adjust for these eventual changes.
Source: Norwegian Water and Energy Board (1994) and Bye et al (1995).

When investment in a power plant is first made, capital costs are **sunk**. Let K_{k0} represent the amount of initial capacity of technology *k* in a country. The age distribution among the individual plants is not known initially, but it is assumed that the average age and corresponding average remaining lifetime, N_k, can be estimated. For nuclear plants, the lifetime depends on political constraints concerning resolutions and plant closures. Nuclear power capacity is assumed to be constant over the simulation period. The existing hydropower and wind power capacities are also assumed to have lifetimes which run over and beyond the entire period.

Since the individual plants are the same size and phase out uniformly, capacity depreciates linearly, with a maximum lifetime of $2N_k$. The remaining old capacity for technology *k* (K_{kt}) is therefore

(31) $$K_{kt} = (1 - \frac{t}{2N_k})K_{k0}.$$

If demand is large enough, new capacity will be generated. The regional distribution of the developments in demand and costs will determine in which country and in which technologies it is profitable to invest. The long run marginal cost ($LRMC_k$) of producing electricity using technology *k* in a country is then

(32) $$LRMC_k = (\Phi_k + \frac{PE_k}{V_k} + FC_k),$$

where FC_k is the sum of fixed capital costs and plant-independent costs, calculated in NOK/kWh.

3.2. Electricity Demand

Consumer demand for an energy good can be determined by maximizing the consumer's utility function, subject to a budget constraint. From this optimization problem, the demand function, which depends upon relative prices and real income, can be derived. Similarly, producer demand for energy is found by maximizing profit (operating surplus). Assuming profit maximization, it can be shown that total energy demand (E_j) is a function of production quantity and relative factor prices. In the model, log linear demand functions are assumed. The demand for electricity in production sector *j* in a country is, therefore

(33) $$E_j = a_j \alpha_{nj} P_{nj}^{-1} [\prod_n P_{nj}^{\alpha_{nj}}] X_j, \qquad n = E, F, K, L, M; \forall j$$

where, recall, X_j stands for the production level in sector *j*, a_j is a constant, and where α_{nj} are the price elasticities.

In the present model version, only two energy goods are specified, heating oil and electricity. We have not yet succeeded in estimating substitution between other energy goods. It may be possible later to include in the model district heating and natural gas as independent energy goods for end-use. The data used in the model are updated to 1991, and all prices are in constant 1991 prices. Data for household demand, purchaser (end-use) prices, total consumption, and the estimated elasticities are used to calibrate the constant (a_j) which appears in the electricity demand function. The household sector is modeled as in the partial model.

4. Data Requirements

The old version of the Nordic model contains electricity and fuel oil demand levels, energy prices and a detailed description of electricity production (including inputs of fuel oil, electricity, coal, biofuels, uranium, etc.), transmission and trade. For this extended model, we needed to build an extensive database (six sector aggregation) for each Nordic country in the base year (1991). Table 4.1 lists the main data collected and their sources for each country.

Table 4.1 Data collected for use in NORMEN and their sources

DATA	SOURCE
1. supply and final demand of goods and services including: -supply from domestic production -supply from imports -supply from import duties -deliveries for intermediate production -deliveries to private consumption -deliveries to investment -deliveries to changes in stocks -deliveries to export	**NOR**: National Accounts-aardat mai94a database; 1991 data **SWE**: Statistics Sweden (1994a); 1991 data **DEN**: Danish Economic Council (1995b), Norge-06117 database; 1990 data **FIN**: Statistics Finland (1995b); 1991 data

DATA	SOURCE
2. sectoral data including: -gross production -intermediate inputs -indirect taxes on production -taxes on E, F inputs -imports/exports -public/private consumption -hours worked -hourly wage -employer tax rate -gross investment -real fixed capital stock -depreciation -operating surplus	**NOR**: National Accounts-aardat mai94a database; 1991 data **SWE**: Statistics Sweden (1994a); 1991 data; capital stock data from (1994b) **DEN**: Danish Economic Council (1995b), Norge-06117 database, 1990 data; and Danmarks Statistik (1995) **FIN**: Statistics Finland (1995b), 1991 data
3. input-output tables	**NOR**: Statistics Norway's MSG-5 model, 1991 data **SWE**: National Institute for Economic Research (1996), 1991 data **DEN**: Danmarks Statistik (1994),1990 data **FIN**: Statistics Finland (1995a), 1992 data
4. consumption parameter estimates -marginal budget shares -minimum consumption expenditures	**NOR**: Aasness and Holtsmark (1993), 1991 data **SWE**: National Institute for Economic Research (1996), avg. 1970-1992 **DEN**: Danish Economic Council (1995a), 1990 data **FIN**: Bank of Finland (1990), 1985 data -FIN marginal budget share approximated by NOR
5. trade elasticity estimates -export: demand and price elasticities -import: price elasticities	**NOR**: Lindquist (1993) for export elasticities; Naug (1994) for import, 1991 data **SWE**: National Institute of Economic Research (ISMOD model) for export elasticities, 1991 data **DEN**: Danish Economic Council (1994) **FIN**: none located, approximated by NOR and SWE estimates
6. population projections	**NOR, SWE, DEN**: Nordic Statistics (1995) **FIN**: Statistics Finland (1995c)

5. Solving the Model

The model is solved with GAMS, (General Algebraic Modeling System), see Brooke et al. (1992). The optimization method used is the same as in the partial Nordic energy market model, i.e. maximizing total Nordic consumer and producer surplus in the electricity market for each year. It would be better to use discounted consumption over the entire period, but this is not possible since this version of the model does not permit optimization over the whole simulation period. A result of the chosen solution method is that some of the variables fluctuate significantly around the trend, such that interpreting the short term results may prove problematic. However, the long term behavior of the model is quite robust.

5.1. NORMEN Results

The reference scenario

The NORMEN reference scenario period used for this analysis is 1991-2030. The most important macro conditions set are the following: The world market growth of industrial products is 1.5% per annum (p.a.). However, for metals and pulp paper, i.e. the most electricity-intensive Nordic industries, world market growth is assumed to decline by 0.5% p.a. Growth in services is set at 2.5%, which is higher than for industrial products due to long term trends in consumption. Another important condition of the model is that technological progress is assumed to be 0.75% p.a. for industries and 0.5% p.a. for services. In the reference scenario, all taxes are fixed at their 1991 levels. Every Swedish nuclear reactor is phased out after 40 years' use, which is assumed to be a reactor's profitable lifetime. Perfect competition is assumed in the Nordic electricity market. The reference scenario will be compared with scenarios which feature higher CO_2 taxes and/or the phasing out of each Swedish nuclear reactor after 25 year's use. These two alternatives are chosen because they will greatly impact the electricity price since thermal and nuclear electricity comprise more that half of total Nordic electricity capacity. In this context, it is interesting to study the interplay between the electricity market and the rest of the economy as a whole. This was impossible to do with the partial Nordic energy market model.

In the reference scenario, average annual growth rates in the Nordic economies during 1995-2030 are as follows: 1.6% in Norway, 1.7% in Sweden, 1.5% in Denmark and 1.4% in Finland, as can been seen in table 5.1. This table also shows how sectoral growth patterns vary over the scenario period. The greatest fluctuations arise in the combined Norwegian sector sea transport/oil production, due to this sector's exogenous production path (which rises until 2005 and then falls). In Norway, Sweden and Finland, the industrial sectors grow faster than the service sector, while the opposite happens in Denmark.

Table 5.1 Sectoral production growth, percent

	Reference scenario				Swedish nuclear reactor phase out after 25 years				CO_2 tax scenario				CO_2 tax scenario and Swedish nuclear phase out after 25 years			
	1995 to 2005	2005 to 2015	2015 to 2030	1995 to 2030	1995 to 2005	2005 to 2015	2015 to 2030	1995 to 2030	1995 to 2005	2005 to 2015	2015 to 2030	1995 to 2030	1995 to 2005	2005 to 2015	2015 to 2030	1995 to 2030
Metals, Norway	0,05	1,36	0,74	0,72	0,01	1,15	0,84	0,69	-0,01	1,33	0,78	0,71	-0,05	1,34	0,82	0,72
Pulp and paper, Norway	1,04	1,99	1,21	1,39	1,02	1,88	1,28	1,37	1,06	2,02	1,25	1,42	1,01	2,05	1,28	1,42
Other industries, Norway	2,54	2,81	2,18	2,46	2,53	2,76	2,21	2,46	2,55	2,81	2,18	2,47	2,53	2,81	2,20	2,47
Services, Norway	2,21	1,48	1,37	1,64	2,21	1,46	1,37	1,64	2,14	1,47	1,38	1,62	2,17	1,44	1,37	1,62
Sea transport and oil, Norway	1,27	-1,42	-0,70	-0,35	1,26	-1,45	-0,67	-0,35	1,33	-1,43	-0,71	-0,34	1,29	-1,40	-0,68	-0,33
Sum, Norway	2,10	1,49	1,42	1,63	2,10	1,46	1,43	1,63	2,08	1,47	1,42	1,62	2,08	1,46	1,42	1,62
Metals, Sweden	1,60	1,79	1,72	1,70	1,66	1,71	1,73	1,70	1,63	1,87	1,82	1,78	1,71	1,94	1,68	1,76
Pulp and paper, Sweden	0,96	1,04	1,00	1,00	1,01	0,93	1,04	1,00	1,01	1,17	1,12	1,10	1,08	1,24	0,98	1,08
Other industries, Sweden	2,35	2,03	1,89	2,06	2,35	2,02	1,90	2,06	2,36	2,04	1,90	2,07	2,36	2,05	1,89	2,07
Services, Sweden	1,67	1,53	1,52	1,57	1,63	1,52	1,55	1,57	1,68	1,53	1,49	1,56	1,63	1,51	1,55	1,56
Chemical industries, Sweden	1,79	1,62	1,55	1,64	1,83	1,60	1,54	1,64	1,78	1,64	1,60	1,66	1,84	1,68	1,52	1,66
Sum, Sweden	1,83	1,66	1,62	1,69	1,80	1,65	1,64	1,69	1,84	1,67	1,61	1,69	1,81	1,66	1,63	1,69
Metals, Denmark	1,05	0,97	1,07	1,04	0,96	0,97	1,13	1,03	1,11	0,94	1,04	1,03	1,07	0,84	1,16	1,04
Food, beverage and chemical industries, Denmark	1,43	1,21	1,29	1,31	1,41	1,20	1,31	1,31	1,43	1,19	1,28	1,30	1,40	1,19	1,31	1,30
Other industries, Denmark	1,69	1,25	1,35	1,41	1,66	1,23	1,37	1,41	1,67	1,24	1,34	1,41	1,64	1,24	1,36	1,41
Services, Denmark	2,08	1,46	1,49	1,65	2,12	1,46	1,47	1,65	2,05	1,50	1,51	1,66	2,07	1,55	1,45	1,66
Sum, Denmark	1,82	1,35	1,40	1,51	1,83	1,34	1,40	1,51	1,81	1,37	1,41	1,51	1,81	1,39	1,39	1,51
Metals, Finland	2,65	1,87	1,48	1,92	2,54	1,92	1,51	1,92	2,49	1,96	1,27	1,81	2,35	1,87	1,42	1,81
Pulp and paper, Finland	0,45	0,39	0,23	0,34	0,31	0,44	0,29	0,34	0,27	0,53	-0,03	0,22	0,04	0,44	0,19	0,22
Other industries, Finland	1,94	1,55	1,24	1,53	1,93	1,55	1,25	1,53	1,94	1,56	1,22	1,52	1,92	1,55	1,24	1,52
Services, Finland	1,48	1,40	1,20	1,34	1,51	1,37	1,21	1,34	1,56	1,39	1,25	1,38	1,57	1,42	1,23	1,38
Chemical industries, Finland	1,84	1,46	1,25	1,48	1,80	1,48	1,26	1,48	1,78	1,49	1,17	1,44	1,73	1,46	1,23	1,44
Sum, Finland	1,58	1,41	1,19	1,36	1,59	1,39	1,20	1,36	1,62	1,42	1,21	1,38	1,61	1,43	1,20	1,38

In the reference scenario, average annual consumption grows by 2.4% in Norway, 2.2% in Sweden and Denmark, and 1.3% in Finland, as reported in table 5.2. One of the main reasons for this particularly low Finnish consumption growth is that the long run balance of trade is exogenous to the model, such that imports equal exports. In the base year, Finland had a small trade deficit, while the other Nordic countries had surpluses. Therefore, less of BNP growth is allocated to consumption in Finland than in the other countries. Consumption of services increases by a bit more than goods consumption in all the countries, which is due to the higher marginal propensity to consume services.

Nordic exports grow on average by 1.2-1.8% p.a., while Nordic imports grow by between 1.2-2.0% p.a. Investment increases by 0.6% p.a. (in Norway) to 1.9% p.a. The low investment growth in Norway is mainly due to the exogenous contraction of the oil sector from year 2005, which results in lower capital demand.

Table 5.2 Consumption growth, percent

	Reference scenario				**Swedish nuclear reactor phase out after 25 years**				**CO_2 tax scenario**				**CO_2 tax scenario and Swedish nuclear phase out after 25 years**			
	1995 to 2005	**2005 to 2015**	**2015 to 2030**	**1995 to 2030**	**1995 to 2005**	**2005 to 2015**	**2015 to 2030**	**1995 to 2030**	**1995 to 2005**	**2005 to 2015**	**2015 to 2030**	**1995 to 2030**	**1995 to 2005**	**2005 to 2015**	**2015 to 2030**	**1995 to 2030**
Goods, Norway	3,73	1,86	1,55	2,26	3,75	1,84	1,52	2,24	3,51	1,81	1,56	2,18	3,59	1,76	1,52	2,17
Services, Norway	4,03	1,97	1,62	2,41	4,06	1,96	1,59	2,39	3,80	1,92	1,63	2,33	3,88	1,87	1,59	2,32
Sum, Norway	3,94	1,94	1,60	2,36	3,97	1,92	1,57	2,35	3,71	1,89	1,61	2,29	3,79	1,84	1,57	2,28
Goods, Sweden	2,18	1,76	1,76	1,88	2,08	1,71	1,86	1,88	2,16	1,76	1,68	1,84	2,03	1,67	1,86	1,85
Services, Sweden	2,95	2,24	2,12	2,39	2,82	2,18	2,25	2,39	2,92	2,23	2,03	2,34	2,76	2,13	2,25	2,36
Sum, Sweden	2,63	2,05	1,98	2,19	2,52	1,99	2,10	2,19	2,61	2,04	1,90	2,14	2,46	1,94	2,10	2,16
Goods, Denmark	3,00	1,64	1,70	2,05	3,12	1,62	1,65	2,06	2,90	1,71	1,75	2,07	2,91	1,89	1,58	2,05
Services, Denmark	3,24	1,75	1,78	2,19	3,37	1,72	1,73	2,19	3,14	1,82	1,84	2,20	3,15	2,00	1,66	2,18
Sum, Denmark	3,17	1,72	1,76	2,15	3,30	1,69	1,71	2,16	3,07	1,79	1,81	2,16	3,08	1,97	1,64	2,15
Goods, Finland	0,96	1,72	1,17	1,27	0,98	1,69	1,18	1,27	0,71	1,66	1,33	1,25	0,76	1,73	1,25	1,25
Services, Finland	0,99	1,76	1,19	1,30	1,01	1,73	1,20	1,30	0,73	1,71	1,35	1,28	0,78	1,78	1,27	1,28
Sum, Finland	0,98	1,75	1,18	1,29	1,00	1,71	1,19	1,29	0,73	1,69	1,35	1,27	0,77	1,76	1,27	1,27

Electricity wholesale prices in the reference scenario increase from 0.17-0.19 Norwegian kroner per kWh (NOK/kWh) in 1991 to 0.26-0.29 NOK/kWh in 2030 (1991 prices), as illustrated in figure 5.1. Up until the year 2000, there is a sharp increase in electricity prices. This is due to higher electricity demand combined with a lack of new profitable electricity generation projects. The prices rise but not yet to a level where large scale investment in new thermal generators is profitable. From 2000-2010, the price level is almost constant due to massive profitable investments in new combined cycle gas generation. After the year 2010, there is a period with increasing wholesale prices because all available natural gas, which is exogenously given, is used for electricity generation. In addition, beginning in 2012, the elimination of Swedish nuclear power becomes an important contributor to the rising electricity price level. The price increase stops and stabilizes around the year 2020, when it reaches the level where investment in the back-stop technology, coal-dust, become profitable. Consumer electricity prices follow the developments in the wholesale market, see table 5.3. The industrial sectors face lower electricity prices than do households and the service sectors due to lower consumption taxes, transmission and distribution costs. Danish households pay considerably more for electricity than do the other Danish sectors due to very high electricity taxes.

Figure 5.1 Wholesale electricity prices, Norwegian kroner (1991 prices),[9] reference scenario

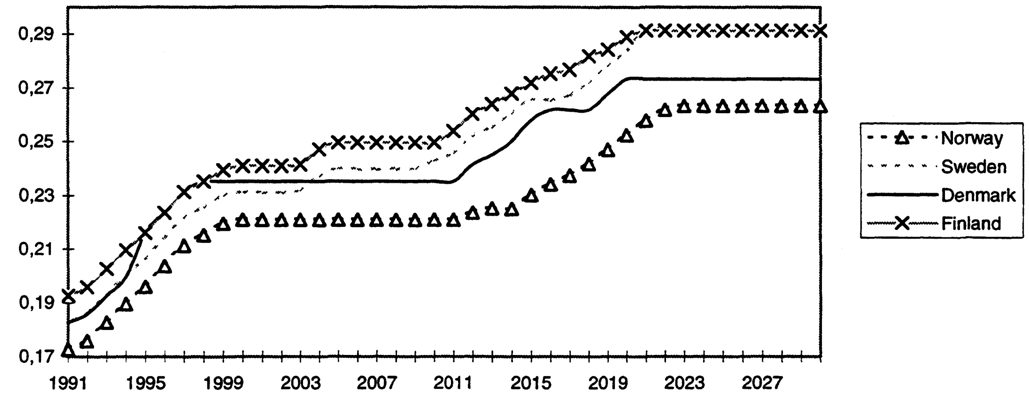


Table 5.3 Electricity consumer prices in Norwegian 1991 kroner, excluding VAT

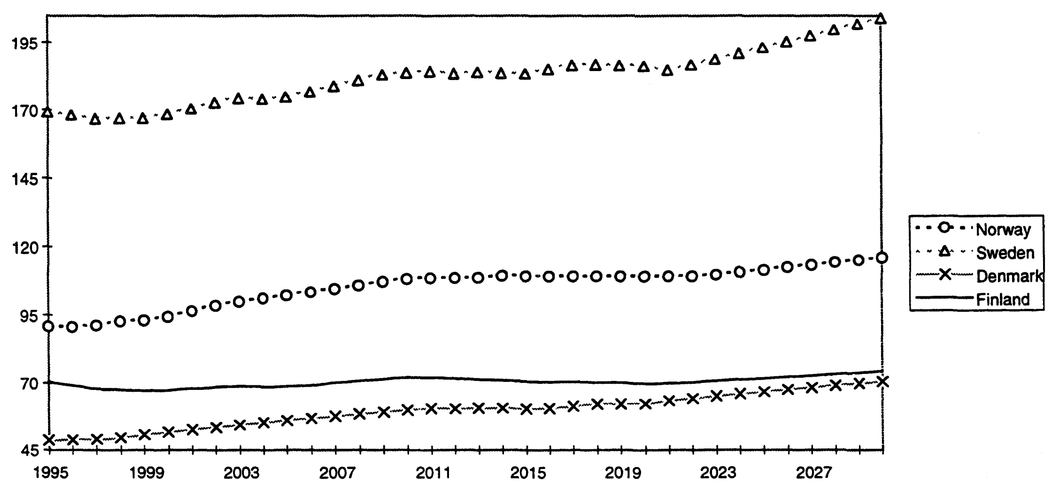
		Reference scenario			Swedish nuclear phase out after 25 years			CO_2 tax scenario			CO_2 tax scenario and Swedish nuclear phase out after 25 years		
		2000	2015	2030	2000	2015	2030	2000	2015	2030	2000	2015	2030
Metals	Norway	.28	.29	.32	.28	.32	.34	.37	.40	.44	.38	.41	.44
Metals	Sweden	.25	.29	.31	.27	.31	.31	.34	.37	.42	.35	.39	.42
Metals	Denmark	.28	.30	.31	.28	.31	.31	.37	.40	.43	.38	40	.43
Metals	Finland	.28	.31	.33	.30	.32	.33	.37	.40	.43	38	.41	.43
Pulp and paper	Norway	.30	.31	.34	.30	.34	.36	.39	.42	.46	.40	.43	.46
Pulp and paper	Sweden	.25	.29	.31	.26	.31	.31	.34	.37	.42	.35	.39	.42
*Pulp and paper	Denmark	.28	.30	.31	.28	.31	.31	.37	.40	.43	.38	.40	.43
Pulp and paper	Finland	.28	.31	.33	.29	.32	.33	.37	.40	.43	.38	.41	.43
Chemicals	Sweden	.27	.31	.33	.28	.33	.33	.36	.39	.44	.37	.41	.44
Chemicals	Finland	.32	.35	.37	.33	.36	.37	.41	.44	.47	.42	.45	.47
Other industries	Norway	.37	.38	.41	.37	.41	.43	.46	.49	.53	.47	.50	.53
Other industries	Sweden	.34	.38	.40	.35	.40	.40	.43	.46	.51	.44	.48	.51
Other industries	Denmark	.32	.34	.35	.32	.35	.35	.41	.44	.47	.42	.44	.47
Other industries	Finland	.32	.35	.37	.33	.36	.37	.41	.44	.47	.42	.45	.47
Services	Norway	.42	.43	.46	.42	.46	.48	.51	.54	.58	.52	.55	.58
Services	Sweden	.42	.46	.48	.43	.48	.48	.51	.54	.59	.52	.56	.59
Services	Denmark	.43	.45	.46	.43	.46	.46	.52	.55	.58	.53	.55	.58
Services	Finland	.43	.46	.48	.44	.47	.48	.52	.55	.58	.53	.56	.58
Households	Norway	.45	.46	.49	.45	.49	.51	.54	.57	.61	.55	.58	.61
Households	Sweden	.50	.54	.56	.51	.56	.56	.59	.62	.67	.60	.64	.67
Households	Denmark	.75	.77	.78	.75	.78	.78	.84	.87	.90	.85	.87	.90
Households	Finland	.43	.46	.48	.44	.47	.48	.52	.55	.58	.53	.56	.58
Wholesale	Norway	.22	.23	.26	.22	.26	.28	.31	.34	.38	.32	.35	.38
Wholesale	Sweden	.23	.27	.29	.24	.29	.29	.32	.35	.40	.33	.37	.40
Wholesale	Denmark	.24	.26	.27	.24	.27	.27	.33	.36	.39	.34	.36	.39
Wholesale	Finland	.24	.27	.29	.25	.28	.29	.33	.36	.39	.34	.37	.39

* N.B. For Denmark, the pulp and paper sector is replaced by the food, beverage/tobacco and chemical industries in this model.

[9] 1 USD=approx 6.4 NOK

In 1991, Nordic electricity consumption was 343 TWh. In the reference scenario, it grows to 465 TWh in 2030, which corresponds to an average growth of about 0.8% p.a., see figure 5.2. The growth patterns vary significantly across the countries. Electricity consumption grows by 7% in Norway, 19% in Finland, 44% in Sweden and 119% in Denmark. One reason for these large differences is that the degree of electricity market regulation varied greatly among Nordic countries in the base year (1991). In 1991, Danish electricity prices were high and there was an abundance of generation capacity. Introducing (perfect) competition to the Nordic electricity market results in lower prices and thus boosts electricity consumption. The sectoral consumption results are reported in table 5.4.[10] The growth in electricity consumption is stronger in households and service sectors than in industries. The most electricity-intensive industries reduce their consumption due to the higher prices, while other industries experience a small increase in electricity consumption.

Figure 5.2 Electricity consumption in the Nordic countries in TWh, reference scenario



[10] NB: Losses in electricity distribution are allocated to the service sectors

Table 5.4 Electricity consumption, TWh.*

		Reference scenario			Swedish nuclear reactor phase out after 25 years			CO_2 tax scenario			CO_2 tax scenario and Swedish nuclear phase out after 25 years		
		2000	2015	2030	2000	2015	2030	2000	2015	2030	2000	2015	2030
Metals	Norway	8,79	8,29	7,04	8,77	7,35	6,63	6,43	5,7	5,01	6,21	5,63	5,01
Metals	Sweden	8,03	7,82	7,81	7,77	7,15	7,81	5,71	5,75	5,7	5,54	5,53	5,67
Metals	Denmark	5,69	5,67	5,83	5,69	5,37	5,83	4,25	4,23	4,27	4,12	4,21	4,28
Metals	Finland	2,81	2,87	2,83	2,71	2,77	2,83	2,11	2,17	2,11	2,02	2,09	2,11
Pulp and paper	Norway	3,2	3,28	2,98	3,2	2,95	2,83	2,42	2,35	2,21	2,34	2,33	2,21
Pulp and paper	Sweden	18,45	16,45	15,13	17,84	14,99	15,12	12,89	11,91	10,9	12,52	11,48	10,85
*Pulp and paper	Denmark	2,42	2,35	2,34	2,42	2,24	2,34	1,8	1,75	1,72	1,75	1,76	1,71
Pulp and paper	Finland	11,85	10,11	8,67	11,37	9,73	8,65	8,92	7,63	6,39	8,44	7,28	6,39
Chemicals	Sweden	6,31	6,17	6,24	6,11	5,68	6,24	4,73	4,75	4,72	4,6	4,55	4,72
Chemicals	Finland	2,6	2,6	2,64	2,53	2,53	2,64	2,03	2,05	2,08	1,97	2	2,08
Other industries	Norway	14,12	16,68	17,92	14,14	15,3	17,13	11,32	12,7	13,94	11,05	12,58	13,93
Other industries	Sweden	19,72	21,1	22,82	19,17	19,62	22,82	15,6	16,97	17,94	15,14	16,23	17,97
Other industries	Denmark	6,14	6,39	6,76	6,14	6,13	6,76	4,69	4,88	5,09	4,57	4,91	5,08
Other industries	Finland	8,97	9,21	9,49	8,73	8,96	9,48	6,92	7,19	7,51	6,76	7,09	7,51
**Services	Norway	31,15	34,1	36,13	31,32	31,67	34,65	26,09	26,97	29,08	25,58	26,79	29
**Services	Sweden	63,53	69,55	78,52	61,87	65,11	78,54	52,5	58,12	63,76	50,98	55,39	64,04
**Services	Denmark	22,75	28,31	34,85	22,75	27,65	34,89	18,28	22,79	27,78	17,9	23,17	27,61
**Services	Finland	19,57	21,6	24,2	19,22	21,15	24,18	15,71	17,52	20,08	15,54	17,45	20,08
Households	Norway	35,86	45,93	51,34	35,93	43,47	49,71	33,47	40,75	46,13	32,96	40,58	46,02
Households	Sweden	52,37	62,23	73,57	51,68	59,16	73,57	46,36	55,47	64,14	45,75	53,31	64,39
Households	Denmark	14,55	17,52	20,71	14,55	17,36	20,74	14,27	17,16	20,21	14,12	17,4	20,12
Households	Finland	21,52	24,17	26,46	21,19	23,74	26,44	21,37	24,33	27,13	21,1	24,22	27,13
Sum	Norway	94,38	109,14	116,00	94,62	101,51	111,52	80,75	89,12	96,82	79,13	88,55	96,64
Sum	Sweden	168,40	183,32	204,09	164,44	171,71	204,11	137,80	152,97	167,16	134,52	146,49	167,64
Sum	Denmark	51,55	60,24	70,50	51,55	58,74	70,57	43,29	50,82	59,07	42,46	51,45	58,82
Sum	Finland	67,32	70,56	74,28	65,75	68,89	74,21	57,06	60,89	65,30	55,82	60,14	65,30
Sum	Nordic	381,65	423,26	464,87	376,36	400,85	460,41	318,89	353,79	388,36	311,94	346,63	388,40

* Losses in electricity distribution is allocated to service sectors

** For Denmark, the pulp and paper sector is replaced by the food, beverage/tobacco and chemical industries in this model.

Table 5.5 Electricity production, TWh

	Reference scenario				Swedish nuclear reactor phase out after 25 years				CO_2 tax scenario				CO_2 tax scenario and Swedish nuclear phase out after 25 years			
	2000	**2010**	**2020**	**2030**	**2000**	**2010**	**2020**	**2030**	**2000**	**2010**	**2020**	**2030**	**2000**	**2010**	**2020**	**2030**
Hydro power, Norway	116,5	116,5	122,0	122,0	116,5	122,0	122,0	122,0	122,0	129,5	129,5	129,5	122,0	122,0	122,0	129,5
Wind power, Norway	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Condense, Norway	0,07	0,03	0,02	0,01	0,07	0,03	0,02	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas power, Norway	3,80	27,46	27,89	27,89	13,98	20,43	20,43	20,43	0,00	0,00	4,40	4,40	0,00	0,85	0,85	0,85
Hydro power, Sweden	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30	63,30
Wind power, Sweden	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
Nuclear, Sweden	76,45	76,45	39,18	0,00	57,16	0,00	0,00	0,00	76,45	76,45	39,18	0,00	57,16	0,00	0,00	0,00
*CHP, Sweden	17,64	16,78	15,96	15,18	17,64	16,78	15,96	15,18	5,27	5,01	15,96	15,18	5,27	16,78	15,96	15,18
Condense, Sweden	1,53	0,77	1,91	52,08	1,53	3,81	26,60	51,70	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas turbine, Sweden	0,00	0,00	1,21	0,61	0,00	2,42	1,21	0,61	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas power, Sweden	0,00	0,00	26,01	26,01	0,00	27,50	27,50	27,50	0,00	0,00	0,00	35,49	0,00	10,68	26,68	46,67
Biofuel, Sweden	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,80	5,80	5,80	0,00	5,80	5,80	5,80
Hydro power, Denmark	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Wind power, Denmark	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82	0,82
*CHP, Denmark	20,61	19,60	18,64	17,73	20,61	19,60	18,64	17,73	20,12	19,60	18,64	17,73	20,61	19,60	18,64	17,73
Condense, Denmark	12,27	6,15	11,05	35,48	12,27	6,15	19,22	31,47	0,00	0,00	0,00	0,86	0,00	0,00	0,00	0,90
Gas turbines, Denmark	0,00	0,00	0,21	0,10	0,00	0,41	0,21	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas power, Denmark	9,06	24,41	30,22	30,22	9,06	36,18	36,18	36,18	0,00	0,00	28,90	44,22	0,00	26,83	33,24	36,59
Hydro power, Finland	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38	12,38
Nuclear, Finland	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17	16,17
*CHP, Finland	22,72	21,61	20,55	19,55	22,72	21,61	20,55	19,55	2,33	12,33	20,55	19,55	12,97	21,61	20,55	19,55
Condense, Finland	8,29	4,16	2,09	7,90	8,29	4,16	2,09	7,83	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas turbines, Finland	0,00	0,00	0,59	0,30	0,00	0,00	0,59	0,30	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Gas power, Finland	0,00	16,82	17,11	17,11	3,81	17,11	17,11	17,11	0,00	0,00	4,75	17,11	0,00	0,97	5,65	17,11
Biofuel, Finland	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,80	5,80	5,80	1,22	5,80	5,80	5,80

* Combined heat and power

Table 5.5 reveals that growth in Nordic electricity production over the reference period is 122 TWh. Norway and Denmark increase their production by 39 TWh and 50 TWh, respectively, while Swedish and Finnish growth are significantly smaller, with 15 TWh and 18 TWh. One of the main reasons for such high production growth in Denmark is its ability to import coal relatively cheaply, which leads to its greater coal-fired generation capacity toward the end of the scenario period with quite a lot. Gas fired generation based on Norwegian natural gas is the most important contributor to the production growth in Norway and Sweden. Denmark also uses a lot of Norwegian gas in power generation. In Finland, however, the production growth is mainly based on imported Russian natural gas. In the reference scenario, there is no generation increase based on biofuels, since the price level is not high enough to make such generation investments profitable.

Electricity trade results are presented in table 5.6, and figures 5.3 and 5.4, which show that Norway exports considerable amounts of electricity to Sweden and Denmark over most of the reference period. Sweden exports a lot of power to Finland in the beginning of the period, yet imports significantly from Denmark during 2015-2030 due to the phasing out of its (Sweden's) nuclear plants between 2012-2024. Finland is a net electricity importer over the entire period, but after 2010 imports only 1 TWh from Norway each year, as a result of the Swedish nuclear plant phase out.

Table 5.6 Electricity trade, TWh

	Reference scenario			Swedish nuclear reactor phase out after 25 years			CO_2 tax scenario			CO_2 tax scenario and Swedish nuclear phase out after 25 years		
	2000	**2015**	**2030**	**2000**	**2015**	**2030**	**2000**	**2015**	**2030**	**2000**	**2015**	**2030**
Norway → Sweden	16,33	31,13	31,13	26,28	31,77	30,04	21,84	23,96	26,28	25,17	26,28	26,28
Norway → Denmark	8,76	8,76	1,88	8,76	8,29	0	16,81	16,81	9,91	16,81	14,63	6,55
Norway → Finland	0,88	0,88	0,88	0,88	0,88	0,88	0,88	0,88	0,88	0,88	0,88	0,88
Sweden → Norway	0	0	0	0	0	0	0	0	0	0	0	0
Sweden → Denmark	0	0	0	0	0	0	5,5	0	0	4,19	0	0
Sweden → Finland	6,88	0	0	1,5	0	0	25,3	13,63	0	12,21	0	0
Denmark → Norway	0	0	0	0	0	0	0	0	0	0	0	0
Denmark → Sweden	0	0	15,77	0	15,77	15,77	0	0	14,51	0	15,77	3,81
Finland → Norway	0	0	0	0	0	0	0	0	0	0	0	0
Finland → Sweden	0	0	0	0	1,67	0	0	0	6,58	0	0	6,58

Figure 5.3 Electricity trade flow, TWh, reference scenario

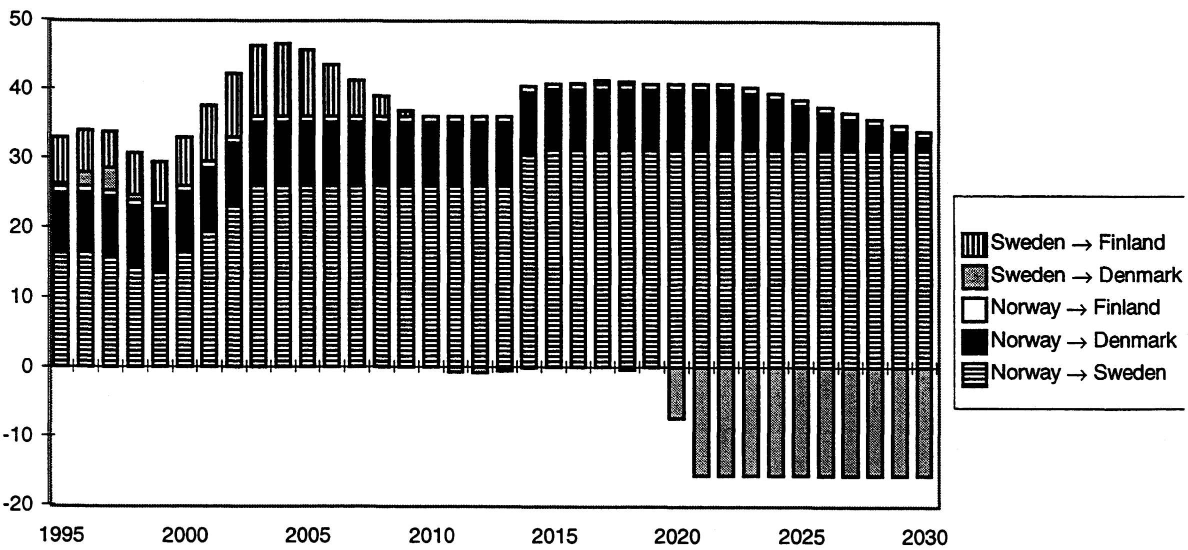
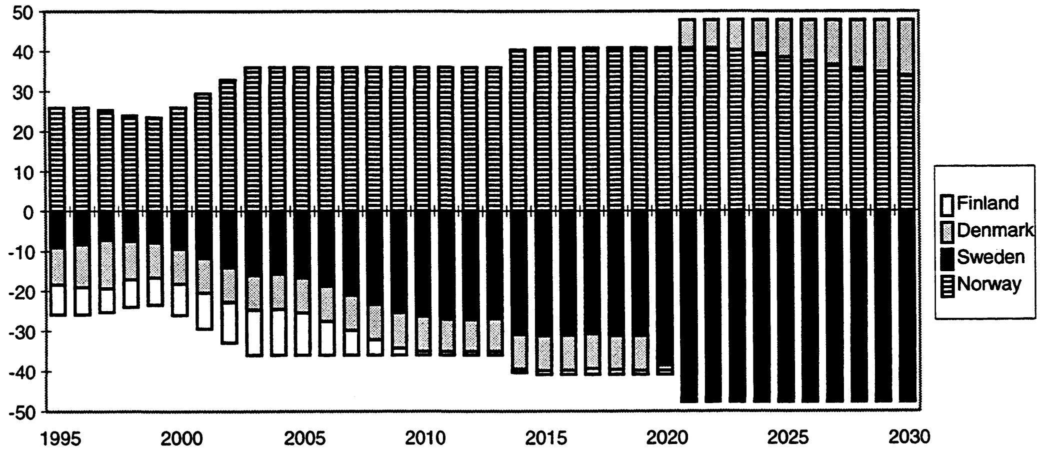
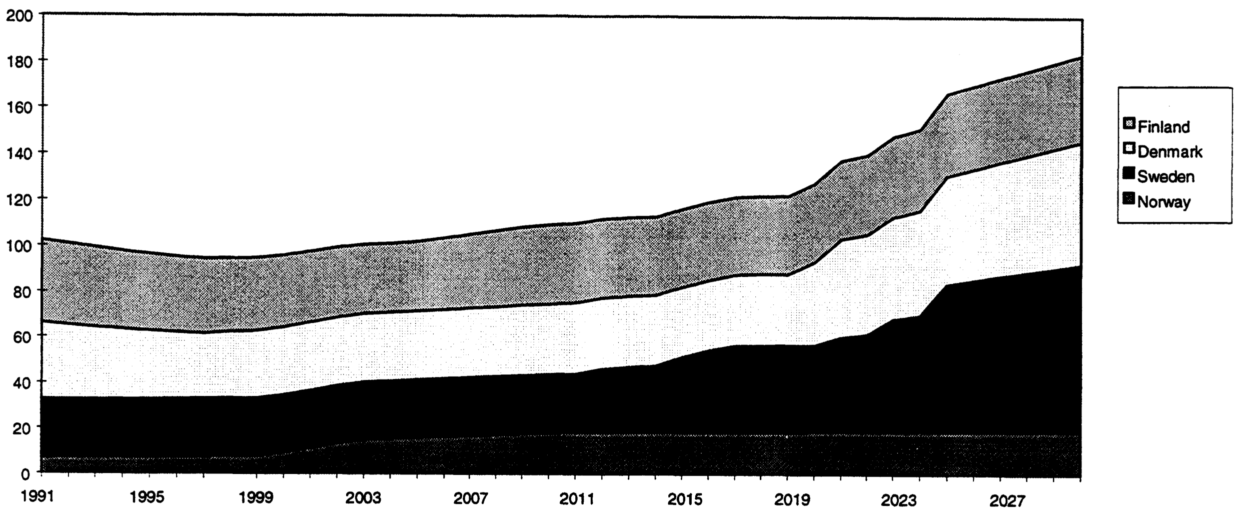


Figure 5.4 Net electricity exports, TWh, reference scenario



In the reference scenario, Nordic CO_2 emissions from electricity generation and stationary use of fuel oil increase from 100 million tons in 1991 to 184 million tons in 2030, see figure 5.5. In the beginning of the period, there is a decline in CO_2 emissions due to the shutting down of old, coal-fired plants in Denmark and Finland. At this time, an additional 10 TWh of Norwegian hydro power capacity is established, which also helps reduce Nordic CO_2 emissions. Between 1998-2012, more gas-fired generation capacity is built in Norway, Denmark and Finland, which leads to gradual increase in CO_2 emissions again. After 2012, when Sweden begins closing down its nuclear power plants, it also begins building natural gas-fired power plants. Toward the end of the period, Nordic coal-fired generation capacity increases, due to limits in the natural gas supply, thereby increasing CO_2 emissions. In short, the main contributor to the large Nordic CO_2 emissions increase in the reference period is the phasing out of Swedish nuclear power, but increased economic activity is also responsible, since CO_2 emissions from the stationary use of fuel are 16 million tons higher in 2030 than in 1991.

Figure 5.5 Nordic CO_2 emissions, million tons, reference scenario



The CO_2 tax scenario

In the reference scenario, the CO_2 emissions almost double over the period. Carbon taxation is a policy instrument often with the aim of reducing CO_2 emissions. To study the efficacy of such an energy policy in a deregulated Nordic framework, we have developed a scenario where Nordic CO_2 taxes are increased from their 1991 level to 350 NOK per ton of CO_2 emissions (about 55 USD) from 1995. All other assumptions are as in the reference scenario.

The macro implications of higher CO_2 taxes include that two input factors of production, electricity and fuel oil, become more expensive. Capital and intermediate input prices also rise due to indirect input-output effects, but these are marginal since electricity and fuel oil are only a minor part of total factor costs for most producers. How the wage reacts to the higher CO_2 taxes depends on whether the substitution or scale effect dominates. In this scenario, the scale effect dominates, production thus falls, as does the wage. All in all, the most important effect of higher carbon taxes is reduced GDP and consumption. In 2030, total Nordic GDP lies 1.1% below the reference scenario, as shown in figure 5.6. In Norway GDP is 1.4% below the reference scenario, see figure 5.7, in Sweden 1.1% below, see figure 5.8, in Denmark 0.8% below, see figure 5.9, while Finnish GDP lies 1.0% below the reference scenario, see figure 5.10. The main reason why Norwegian GDP is the most responsive is that electricity prices there are the most affected by the higher carbon tax.

Figure 5.6 Nordic GDP, deviation from reference scenario, percent

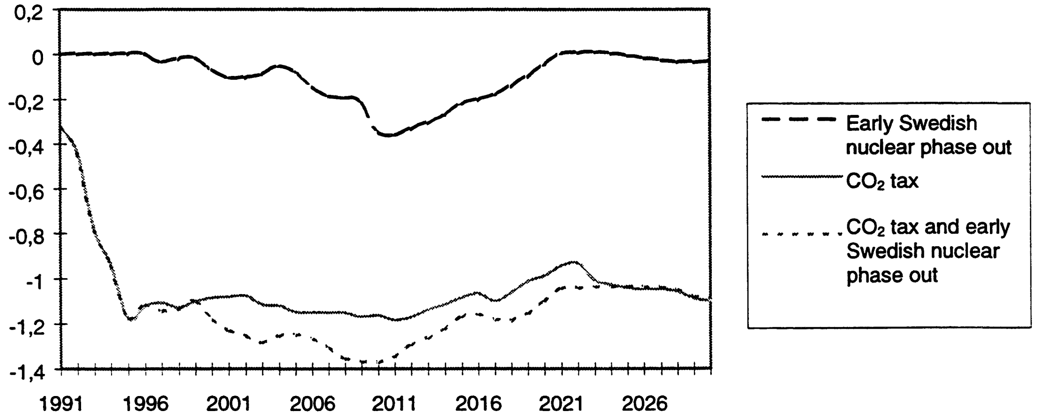


Figure 5.7 Norwegian GDP, deviation from reference scenario, percent

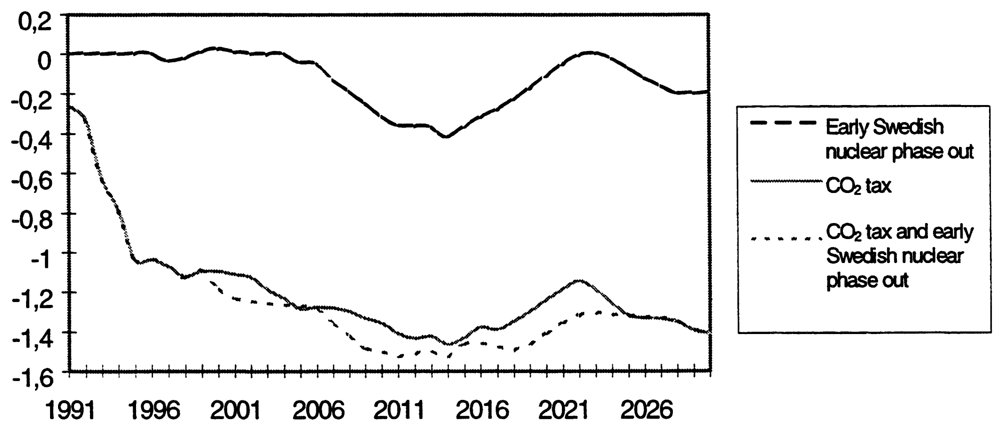


Figure 5.8 Swedish GDP, deviation from reference scenario, percent

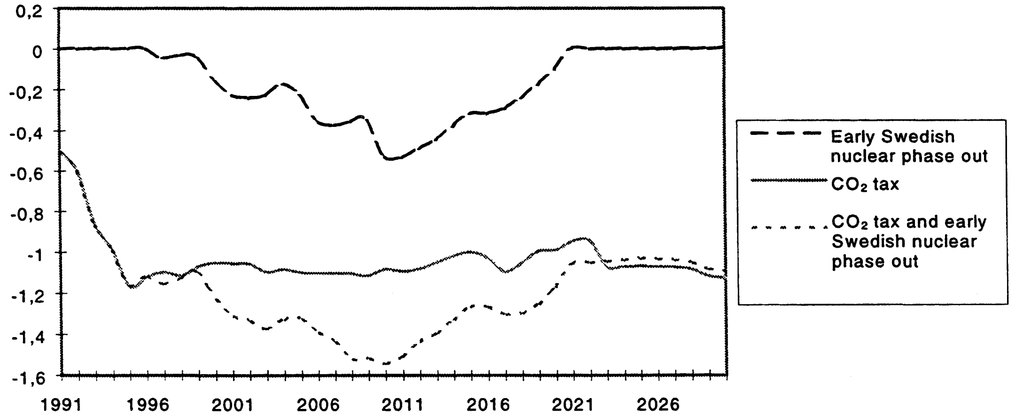


Figure 5.9 Danish GDP, deviation from reference scenario, percent

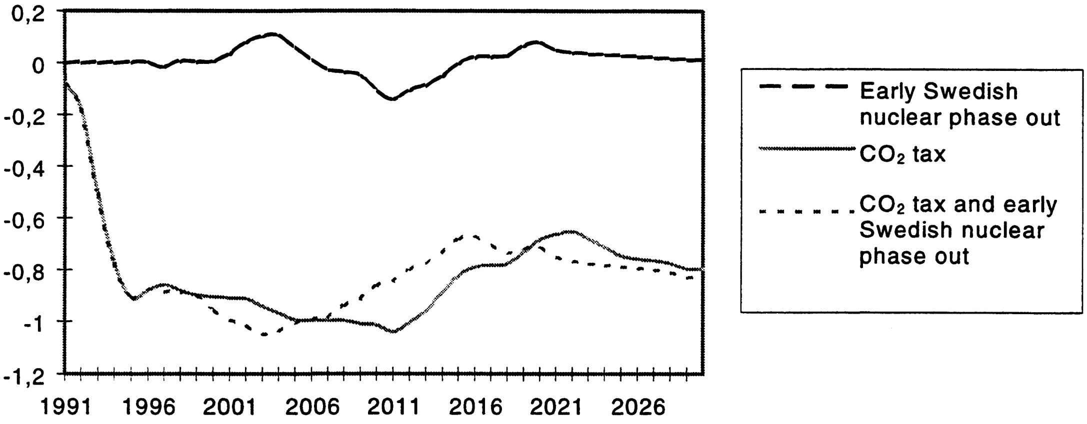


Figure 5.10 Finnish GDP, deviation from reference scenario, percent

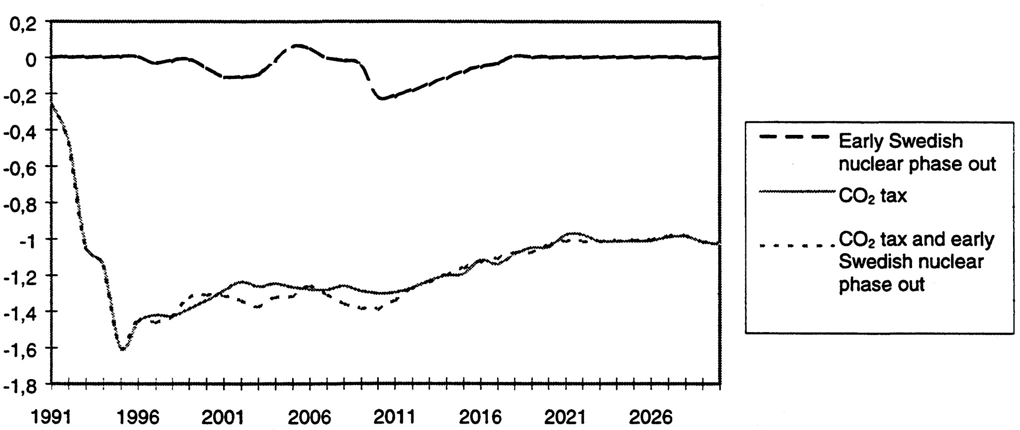


Table 5.7 Deviation from reference scenario for some key macroeconomic variables, percent

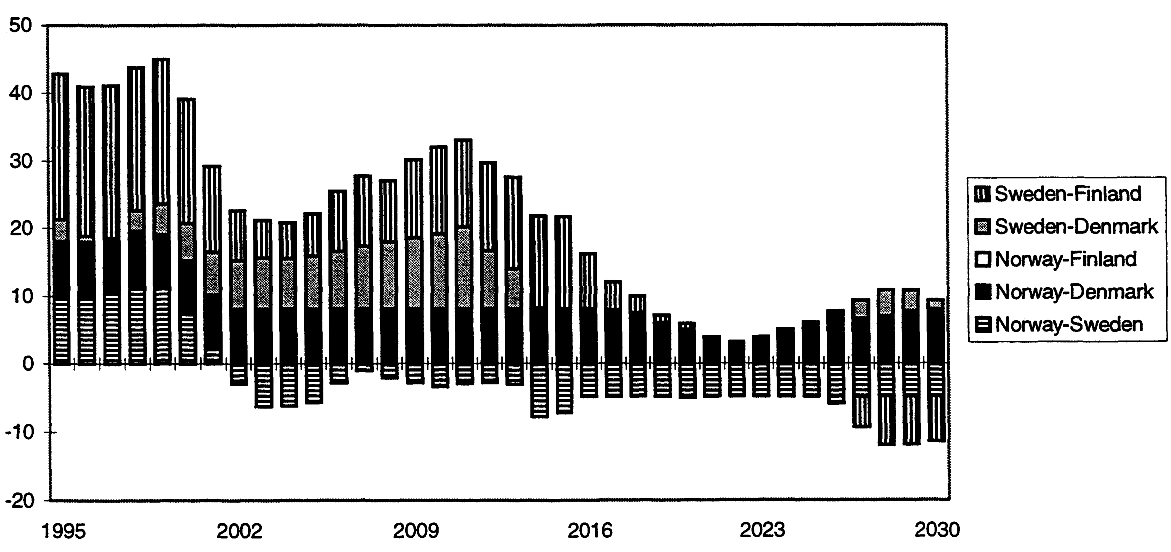
	Swedish nuclear reactor phase out after 25 years				CO_2 tax scenario				CO_2 tax scenario and Swedish nuclear phase out after 25 years			
	2000	2010	2020	2030	2000	2010	2020	2030	2000	2010	2020	2030
Consumption, Norway	0,27	0,50	-0,47	-0,44	1,97	0,35	-0,37	-0,21	2,15	0,74	-0,33	-0,55
GDP, Norway	0,02	-0,31	-0,12	-0,20	-1,09	-1,36	-1,24	-1,41	-1,18	-1,50	-1,41	-1,41
Imports, Norway	0,64	0,51	-0,27	-0,26	1,34	0,68	0,29	0,42	1,55	1,15	0,36	0,15
Exports, Norway	-0,44	-0,84	0,12	0,00	-2,43	-2,33	-1,91	-2,32	-2,69	-2,89	-2,19	-2,06
Investments, Norway	1,50	-0,34	0,01	-0,22	-1,78	-1,92	-0,82	-1,18	-1,67	-1,60	-1,15	-1,23
Capital stock, Norway	0,20	-0,04	-0,19	-0,24	-0,31	-0,77	-0,84	-0,89	-0,30	-0,71	-0,94	-0,99
Consumption, Sweden	0,10	-0,79	-1,26	-0,01	-0,67	-0,56	-1,17	-1,72	-0,42	-2,73	-2,80	-1,18
GDP, Sweden	-0,15	-0,53	-0,11	0,00	-1,05	-1,08	-0,99	-1,13	-1,22	-1,55	-1,17	-1,10
Imports, Sweden	-0,59	-1,42	-0,37	0,03	-0,52	-0,28	-0,90	-1,30	-1,29	-2,38	-1,35	-0,90
Exports, Sweden	0,43	0,61	0,30	-0,04	-2,16	-2,43	-1,03	-0,69	-1,51	-0,50	-0,79	-1,20
Investments, Sweden	-2,82	-4,27	1,93	0,16	-0,31	0,09	-1,13	-1,50	-4,32	-3,34	1,41	-1,38
Capital stock, Sweden	-0,28	-0,78	-0,21	0,01	-0,72	-0,69	-0,87	-1,10	-1,07	-1,69	-1,15	-0,93
Consumption, Denmark	0,01	0,82	1,33	0,20	-2,65	-3,11	-1,61	-1,43	-2,61	-1,44	-0,19	-2,05
GDP, Denmark	0,00	-0,11	0,08	0,01	-0,91	-1,01	-0,68	-0,80	-0,96	-0,87	-0,72	-0,83
Imports, Denmark	0,00	0,96	0,84	0,10	-1,73	-2,17	-0,58	-0,65	-1,70	0,22	-0,21	-1,22
Exports, Denmark	0,00	-0,97	-0,77	-0,10	0,67	0,96	-0,09	-0,22	0,57	-0,91	-0,71	0,25
Investments, Denmark	-0,04	0,87	-1,00	-0,32	-1,69	-1,76	1,10	-0,09	-1,84	3,42	-2,69	-0,31
Capital stock, Denmark	0,00	0,33	0,45	0,06	-1,26	-1,53	-0,72	-0,77	-1,28	-0,56	-0,45	-1,04
Consumption, Finland	0,10	0,98	0,00	0,00	-4,56	-2,82	-1,54	-0,63	-3,99	-1,86	-1,66	-0,63
GDP, Finland	-0,06	-0,22	0,00	0,00	-1,34	-1,30	-1,05	-1,03	-1,31	-1,39	-1,04	-1,03
Imports, Finland	0,23	-0,03	0,00	0,00	-3,58	-2,85	-1,37	-0,57	-2,49	-1,88	-1,27	-0,57
Exports, Finland	-0,65	-0,84	0,00	0,00	1,08	0,00	-1,30	-2,28	-0,74	-1,94	-1,43	-2,28
Investments, Finland	0,53	-2,75	0,01	0,00	0,21	-2,11	-0,97	-1,17	2,39	-1,69	-0,33	-1,17
Capital stock, Finland	0,02	-0,15	0,00	0,00	-1,85	-1,63	-1,07	-0,83	-1,56	-1,45	-1,04	-0,83

One might expect widening GDP differences between the reference scenario and the CO_2 tax scenario over the period. However, this is not the case both because the difference in the electricity prices does not increase and because the growth mechanisms in the model are the same in both scenarios. Total Nordic consumption in 2030 under higher carbon taxes is 1.2% lower than in the reference scenario. One reason why consumption falls by more than does production is that government expenditure and the trade balance are exogenous in the model. Consumption growth in 1995-2030 in the CO_2 tax scenario is as in the reference scenario or slightly lower (less than 0.1% p.a.), see table 5.2.

Table 5.7 shows the differences between the CO_2 tax scenario and the reference scenario for some important macro variables. In every Nordic country, the capital stock is smaller than in the reference scenario. This is because reduced economic activity (GDP) combined with higher CO_2 taxes implies a lower demand for capital as a production factor. Consumption of goods other than electricity is lower in all countries except Norway in the CO_2 tax scenario. The reason why Norwegian (non-electricity) consumption increases in 2000 and 2010 in this scenario is that electricity exports rise. With an exogenous trade balance, this permits greater imports of other goods, which eventually implies higher Norwegian consumption.

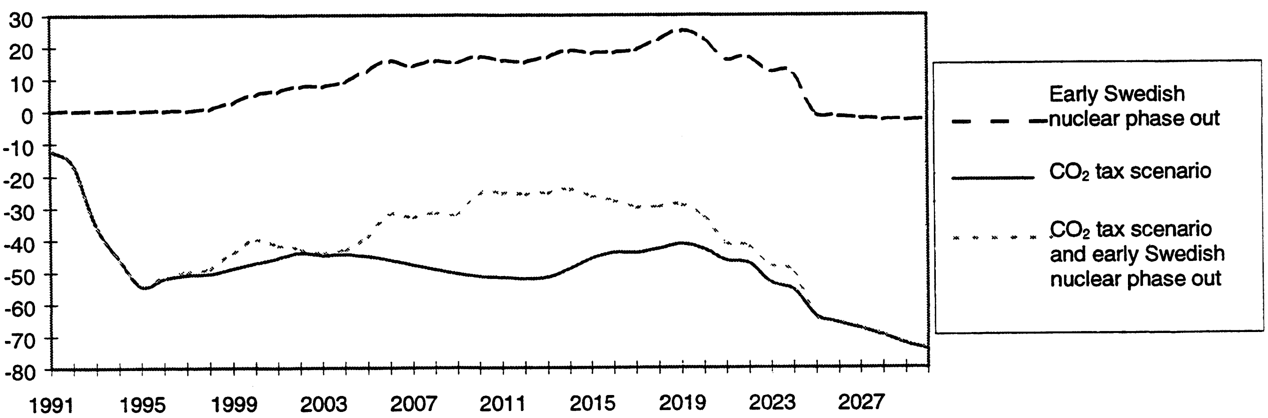
The effects on the electricity market of higher CO_2 taxes are quite dramatic. Wholesale electricity prices in 2030 reach 0.38-0.40 NOK/kWh, which is almost 50% higher than in the reference scenario. The consumer electricity prices rise about the same amount measured in kroner, see table 5.3, but by a lesser amount measured in percent since consumer taxes are unchanged. Although total Nordic electricity consumption increases only by a modest 45 TWh between 1991 and 2030, compared to 122 TWh in the reference scenario,several other interesting effects are visible. Sectoral electricity production patterns change significantly compared to the reference scenario, as reported in table 5.5. Now, in contrast to the reference scenario, there is no increase in coal-fired generation in Sweden and Denmark in the end of the period. Instead, biofueled power plants in Sweden and Finland and hydro power plants in Norway are built. The impact of higher CO_2 taxes on electricity trade depends on whether the initial generation capacity was primarily based on hydro power or fossil fuels. In the base year, Denmark and Finland, whose electricity generation is primarily based on fossil fuels, reduce their net exports of electricity. Norway, on the other hand, increases its net electricity exports due to its almost exclusive generation of hydro power (99%), see figure 5.11.

Figure 5.11 Electricity trade flows, TWh, high CO_2 tax scenario, deviation from reference scenario



In 2030, CO_2 emissions under the high carbon tax scenario are 109 million tons, or a bit more than half of their reference scenario level, as illustrated in figure 5.12. The emissions reduction here is primarily due to the contraction of the electricity producing sector, but also, to a lesser extent, to the reduction in (stationary) fuel oil consumption, compared with the reference scenario. (In 2030, the reduction is 9 million tons.) The percentage reduction in CO_2 emissions in 2030 compared with the reference scenario is greatest in Norway, with 51%. Similarly, Sweden reduces its emissions by 46%, Denmark by 39% and Finland by 27%.

Figure 5.12 Nordic CO_2 emissions, deviation from reference scenario, million tons



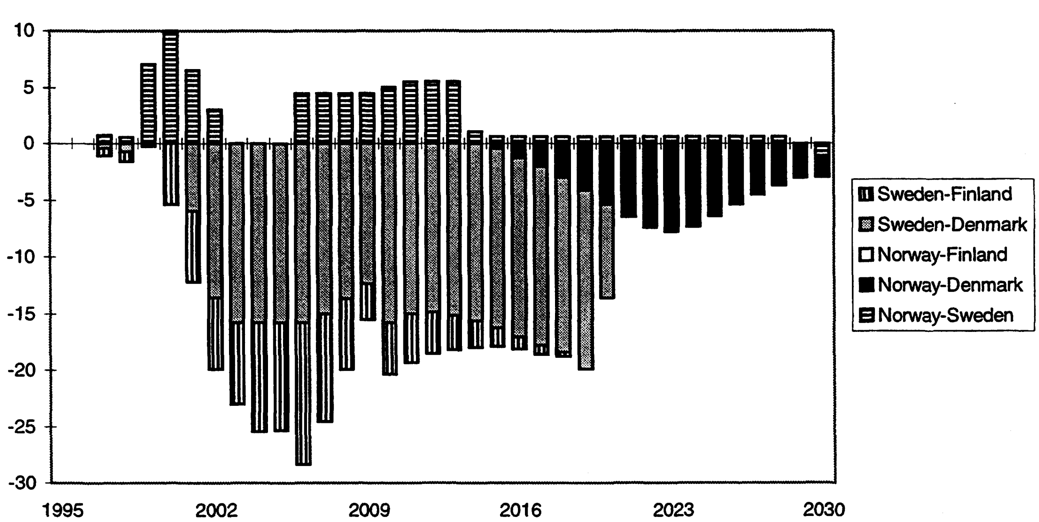
The phasing out of Swedish nuclear power

In 1980, Sweden made political decisions about the future of its nuclear power after holding a referendum. The main point was that all Swedish nuclear power should be eliminated by the year 2010, given that a set of economic conditions were satisfied. Whether this will be carried out in practice remains to be seen. In order to study the effects of this political decision, we re-run the reference and CO_2 tax scenarios, this time eliminating each Swedish nuclear reactor after 25 years, rather than 40 (as in the reference case). All other assumptions of the model remain unchanged.

In both scenarios with 25 year reactor lives (i.e. with an without higher CO_2 taxes), the wholesale electricity price are the same at the end of the period as they were for the corresponding scenarios with 40 year nuclear plant lifetimes. This is because Swedish nuclear power is phased out by 2030 regardless. Therefore, most of the other variables are also nearly identical at the end of the period. However, the developments over the course of the period are significant and are strongest in the scenario without increased CO_2 taxes. Thus, the results from that scenario (early Swedish nuclear phase out without increased carbon taxes) will be focused on here. The biggest rise in wholesale electricity prices per kWh with Swedish reactor phase out after 25 years' use is 0.04 NOK compared to the reference scenario and 0.03 NOK compared with the higher CO_2 tax scenario.

As table 5.4 reveals, total Nordic electricity consumption patterns remain basically unchanged compared to the reference scenario, winding up about 1% lower by the end of the period. Production patterns, however, show more noticeable changes. In Sweden, gas power, CHP, and gas turbine generation methods pick up the slack which results from the earlier nuclear plant shutdowns. The upward trend for these methods starts in about 2010, as opposed to in 2020 for the reference scenario. Denmark also demonstrates a new production pattern, using substantially more gas power beginning in about 2002, rather than stepping up gas power production in 2020, as in the reference scenario. Trade patterns under early Swedish nuclear plant shut down (with base year carbon taxes) are significantly changed, see figure 5.13. Sweden exports considerably less electricity to Finland in the beginning of the period than in the reference scenario, and imports from Finland between 2006-2016, something which does not occur at all in the reference scenario. In addition, as would be expected, Sweden also starts importing electricity from Denmark earlier than in the reference scenario, now starting in 2001 and remaining fairly stable at about 16 Twh for the rest of the period.

Figure 5.13 Electricity trade flows, TWh, early Swedish nuclear phase-out scenario, deviation from reference scenario



CO_2 emissions are affected in two ways by Swedish reactor phase outs: first, power generation based on fossil fuels rises which increases CO_2 emissions. Second, because electricity prices increase, consumers substitute somewhat away from electricity and towards the (stationary) use of fuel oils, which also leads to higher CO_2 emissions, see figure 5.12. The largest reduction in Nordic GDP resulting from the phasing out of Swedish nuclear reactors is around 0.37% compared to the reference scenario and around 0.21% compared to the higher CO_2 tax scenario. In Norway and Sweden, the reduction in GDP is greatest around 2010, when all Swedish nuclear power generation is eliminated. With increased carbon taxes and earlier nuclear plant closures, the largest GDP reduction occurs a few years earlier in Denmark and Finland than in Norway and Sweden.

6. Conclusions

In an earlier partial Nordic energy market model, the interaction between the Nordic electricity market and the rest of the economy was not integrated. NORMEN was designed to take these interaction aspects into account. The energy markets are modeled in the same way as the earlier partial model, while the main elements of the macro module are as in traditional CGE models. To keep the model structure simple, we use elementary functional forms for important macro variables. Most sectors have a Cobb-Douglas production structure with constant returns to scale and no excess profits. Trade (except of electricity) is modeled according to the Armington hypothesis, i.e. domestic and foreign goods are imperfect substitutes. The trade balance and government consumption are treated exogenously. The level of total consumption is determined such that there is equilibrium in the goods markets. NORMEN's model structure, databases and calibration methods are documented in this report.

Using NORMEN, we analyze the effects on the Nordic electricity market and on the Nordic economies of increased CO_2 taxes and/or early Swedish nuclear reactor shut downs. Compared with the earlier partial Nordic energy market model, in NORMEN electricity consumption is more sensitive to electricity price changes because the substitution between energy and other production factors such as labor, capital and intermediates is an integrated part of the model. An increase in the electricity price resulting from higher CO_2 taxes and/or early Swedish nuclear reactor phase out has only modest effects on important macro variables such as GDP and consumption. In the long run, the reduction in GDP is around 1% when the electricity price rises by 50%. This is because the cost of electricity for most sectors is only a small fraction of total factor outlays. Even for the most electricity-intensive sectors in NORMEN, the electricity cost share is not greater than 10%. This means that the price of produced inputs, such as capital and intermediates, changes very little with large electricity price increases. Thus, the amount of capital and intermediates demanded by producers also scarcely changes. By introducing a common Nordic CO_2 tax of 350 NOK (around 55 USD) per ton CO_2, total Nordic stationary CO_2 emissions fall by about 40%. Most of this reduction occurs in the power generation sector (coal, oil, and gas fired). But the use of oil for stationary purposes falls, which also reduces CO_2 emissions.

In future model versions, it is very important to improve the description of the connection between electricity prices and electricity consumption in the production sectors. This version of the model probably exaggerates how strongly electricity consumption reacts to electricity price changes, while the production scale effects may be underestimated. The closure mechanism in this version of the model implies that key variables, such as consumption and investment, vary cyclically around the trend in the short run. In the long run, however, the model is reasonably robust. In any case, the closure mechanism still ought to be improved. One possible way to do this might be to maximize total discounted Nordic consumption over the entire scenario period, rather than maximizing the sum of consumer and producer surplus in the electricity market, as in done in this version of NORMEN. Another possible improvement to the model would be to integrate the variations in electricity demand and production over the day/week/season, something which is an important feature of 'real' electricity markets. Such an improvement is very important in order to describe electricity trade patterns and would better reflect the variation in the short term marginal costs in the interplay especially between hydro power and thermal power.

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Statistics Norway
Research Department
P.O.B. 8131 Dep.
N-0033 Oslo

Tel.: + 47-22 86 45 00
Fax: + 47-22 11 12 38

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