Electricity and emission-permits trade as a means of curbing CO_2 emissions in the Nordic countries

T. Unger [a] and L. Alm [b]

[a] EST, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
E-mail: tung@entek.chalmers.se
[b] Institute for Energy Technology, PO Box 2007, Kjeller, Norway

Received 5 July 1999; revised 4 January 2000

The four Nordic countries Sweden, Denmark, Finland and Norway have fully integrated electricity grids, implying that electricity trade hitherto has accounted for a crucial part of each country's power balance. Electricity trade also provides cost-efficient opportunities for the Nordic countries to either jointly or separately fulfil their CO_2 obligations. Assuming the targets that were agreed upon in (the aftermath of) the Kyoto negotiations in 1997, and establishing scenarios where CO_2-emission-permits trade among the Nordic countries is allowed, it is shown that the value of emission trading is somewhat larger than the corresponding value of electricity trade. Furthermore, if both electricity and emission permits can be traded on a common Nordic market this can lead to amplified economic benefits yielding a gain that exceeds the sum of the separate values of electricity and emission permits trade. It is also shown that the additional costs of fulfilling the Kyoto protocol are small compared to the total costs of the Nordic energy system.

1. Introduction

During the past years increasing awareness concerning the greenhouse gas problem has brought impacts of supply, conversion, distribution and use of energy to the top of the environmental as well as the political agenda. The negotiations in Kyoto in Japan in 1997 led to binding emission targets for a basket of six greenhouse gases for the industrialized countries [1]. However, extensive work remains to be done. Apart from national ratifications of the Kyoto protocol, further agreement should be reached concerning the means to reduce emissions on a global scale. Joint implementation, common action, emission permits trade, taxation policies and so forth can individually or in combination provide the necessary tools for achieving the goals that were defined in Kyoto.

This paper analyses the interactions between trade of electricity and CO_2 emissions permits among the Nordic countries. The objective is to answer three questions: How large are the cost increases when meeting the Kyoto protocol in the Nordic countries? In what way are these cost increases affected by electricity trade and/or emission-permits trade? And how is the burden sharing distributed among the different energy demand sectors within the countries when changing the options for jointly curbing CO_2 emissions?

Today, the Nordic countries are practicing a more or less free trade of electricity among themselves. The grids are fully integrated and synchronized, and trade has occurred since 1915, when Denmark and Sweden first started to exchange power.

On the other hand, the countries are committed to national quotas for emissions of greenhouse gases. These quotas can, when they get tight and binding, impede the countries from being able to exploit the benefits of electricity trade. When countries are trying to meet their CO_2 obligations in an "optimal" way, i.e., minimizing abatement costs, this will create a shadow price on electricity export, thereby reducing the level of electricity trade. The optimal way would be to allow both electricity trade and CO_2 trade, enabling electricity to be produced in the most suitable country and CO_2 abatement occur in the country with the lowest costs for abatement measures.

Similar studies have been carried out for common action among several countries using the same methodology used here (e.g., [2]), but their focus has primarily been on either CO_2 trade or electricity trade, not looking into the contradictions of a system allowing electricity trade but not CO_2 trade. This is the main focus of our work.

This study builds to a large extent on previous work that has been carried out at the Energy Technology Division in Gothenburg and at the Institute for Energy Technology at Kjeller [3]. Apart from extensive data updating and harmonisation, the model has been extended to include Finland, in order to complete the Nordic grid, and the taxation system for the four countries.

2. The Nordic electricity system, trade and deregulation

Electricity production in the four countries is depicted in figure 1.

Total electricity production in 1997 was 145 TWh in Sweden, 112 TWh in Norway, 42 TWh in Denmark and 66 TWh in Finland [4]. The separate power (separate power plants are only producing electricity) and CHP (combined

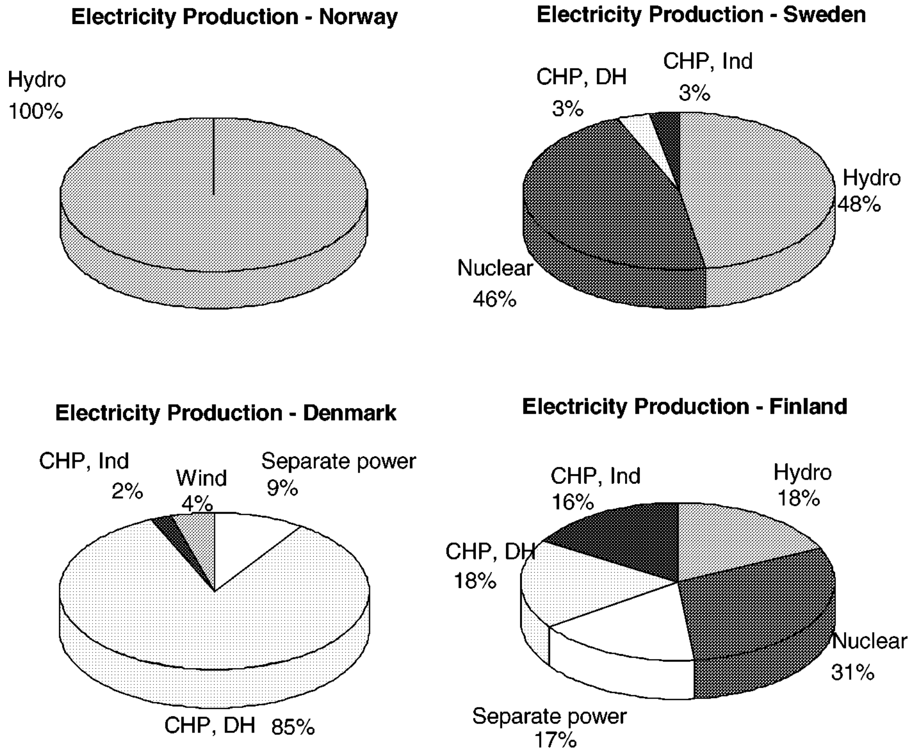

Figure 1. Electricity production in 1997 in the Nordic countries. Combined heat and power (CHP) occurs both in the public district heating grids (DH) and in industrial back-pressure plants (Ind). The relation between CHP, DH and separate power in Denmark is estimated. The sum, however, is from official statistics.

heat and power plants produce electricity as well as district heat) sectors in Denmark are mainly fueled with coal [5]. In Finland, on the other hand, there is a rather even distribution between coal, natural gas and indigenous fuels such as peat and waste liquors [6]. The differences in the supply mix of these production systems create incentives for electricity trade among the countries. In dry years, the over-capacity of fossil fuel systems in Denmark and Finland provides a backup for the annually varying hydropower production in mainly Sweden and Norway. Easily regulated hydropower can also provide cheap peak power to all the countries through diurnal trade. In addition net trade can be profitable when production capabilities in one country are less costly than in the other, counted on long terms, or when existing production capacity in one country can be used by the other country to avoid investments in new capacity.

Norway and Sweden with their high shares of hydropower are normally net exporters of electricity in wet years. Under dry year conditions, the electricity flows the other way, i.e., Finland and particularly Denmark become net exporters. This was very pronounced during the dry year of 1996 when Denmark's electricity production was approximately 20% above the level of 1997, which can be regarded as a more normal year. The deregulation of the Nordic electricity markets (with some exception for Denmark) has strengthened trade mechanisms, thereby enhancing economic benefits. Norway was the first to deregulate (in 1991) followed by Sweden (1996) and Finland (1997) [4].

3. Methodology

In this study the focus is on the technical energy system with its complex composition of components. Thus, only technological system components are described and analyzed. The system is described as a reference-energy system [7] and shown in figure 2 with its system boundaries. It should be noted that figure 2 is used for illustration purposes only. The actual system analyzed here is far more complex and comprehensive. The demand for useful energy, which is exogenous and fixed, is satisfied by small-scale conversion technologies, such as district heat exchangers, electric devices, heat pumps, fossil or bio fuelled furnaces, etc. Demand and end-use energy conversion is on the right-hand side in figure 2. These small-scale technologies are supplied with energy through electricity grids, district heating grids or fuel transport systems, e.g., natural gas distribution pipes. This infrastructure is in turn connected to a vast number of different large-scale conversion technologies, producing either electricity to the public grid, district heat or both (combined power and heat plants). Large-scale energy conversion, as in the case of the small-scale conversion sector, is connected to fuel supply modules on the left-hand side in figure 2. Fuel switching, energy efficiency measures and conservation are also considered.

Energy demand sub-sectors that are contained within the system are the residential/commercial sector (including agriculture) and the industrial sector. Energy production sub-sectors are separate power production, district heat production and industrial back-pressure production. Sepa-

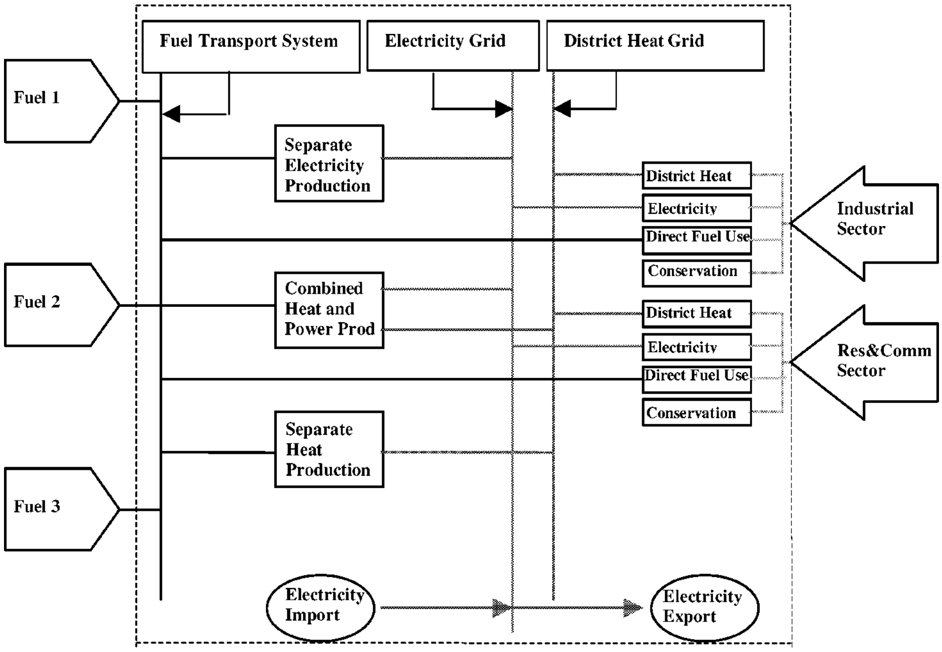

Figure 2. Simplified description of a reference energy system.

rate power means large-scale condensing power units, e.g., hydropower, nuclear power and coal condensing, producing electricity for the public grid. District heat production includes heat plants producing only district heat as well as combined power and heat plants producing electricity to the public grid and district heat for local consumption. Industrial back-pressure contains technologies for producing only process steam and technologies for supplying the industries with process steam and electricity. The electricity can also be supplied to the public grid if this is favorable.

The four countries are connected via import and export of electricity. Thereby, all four energy systems are interconnected. Each country contains all the sub-sectors, previously discussed.

The dotted line in figure 2 indicates the system boundaries of the modeling analysis. Demand for useful energy and cost of primary fuels lie outside the range of influence of the technical system modeled.

For modeling purposes the IEA-MARKAL code [8] is used for describing and optimizing the reference energy system. All technological components and energy activities in figure 2 are described by investment costs, operation and maintenance costs, economic length of lives, technical efficiencies and operation availabilities. The demand for useful energy is satisfied by the least-cost combination of small-scale conversion technologies, transmission and distribution system (fuels, electricity or district heat), large-scale conversion technologies and fuel supply. Thus, the objective function, i.e., the discounted total system cost which is a sum of all investment, O&M and fuel costs within the system, is to be minimized. The problem is further described by a vast number of constraints, for instance plant-capacity limits or upper emissions' levels. Since the objective function and all constraints are expressed mathematically as linear functions, the problem is addressed as a linear programming problem.

All costs referred to in this paper are total discounted system costs under different scenarios. Discounting is performed at a discount rate of seven percent to the year 1990 for the entire modeling period, i.e., from 1990 to 2030. This means that the model produces information only regarding costs incurred on the technical energy system as it is depicted in figure 2. No estimates regarding benefits, e.g., from lower electricity prices or environmentally clean production technologies, by changing the system can be done, let alone that a reduced system cost when comparing two system solutions can be regarded as a "benefit". The modeling is strictly limited to costs. It considers costs and emissions as a descriptor of technology and energy activity. Benefits or environmental disturbances that cannot be expressed in monetary units or as emissions will inevitably be omitted.

4. Data and assumptions

Data have been retrieved from various authorities and research centers in the four countries, such as Institute for Energy Technology in Norway, VTT-Energy in Finland, Risø National Laboratory in Denmark and the Governmental Energy Commission in Sweden.

In the model, Swedish nuclear power is kept at 9.4 GW after shutting down one reactor at the Barsebäck plant (in accordance with the governmental decision in 1991) from the year 2000 on. Nuclear reactors are expected to have a technical length of life of roughly 40 years before the age of the reactor vessel makes further operation impossible. However, 40 years require major refurbishing after 25 years, which already has been proven by older Swedish units. No new Swedish nuclear capacity is allowed in the model. This is also in accordance with the Swedish governmental decision, which is based on a referendum passed in 1980. Thus, the entire nuclear phase-out is completed in 2030. The Finnish reactors can be replaced by new units keeping the total nuclear production capacity at a maximum level of roughly 20 TWh (2650 MW) throughout the entire modeling period.

In Norway new hydropower projects with a total energy contribution of 18.5 TWh (6000 MW) are allowed to develop. These projects are identical to those grouped in the so-called "Category 1" with the addition of projects where concessions are already given. Although another projected 11 TWh (mostly "Category 2" projects) are not permanently prohibited by law, they are not expected be developed because of environmental concerns.[1] In Sweden only three TWh from new hydro capacity (720 MW) is allowed, but these projects are expensive. In Finland only 1.9 TWh of new hydropower capacity is considered feasible (310 GW).

In this study wind power is expected to have a large potential in the Nordic countries. This means very roughly 10–20 TWh, depending on the country. Both on-shore and off-shore locations are taken into consideration, and the costs of the projects are distributed according to regional variations in the wind regime. The cost of wind power is considered to decrease by approximately 30% between the starting year 1990 and 2010, due to technology learning [9]. Today wind power is subsidized in all countries. These subsidies are gradually decreased until 2010 when they finally are completely removed in the model. Decreasing investment costs and CO_2 obligations will make way for wind power, which is why subsidies are needless in the long run.

It is assumed that 10 TWh (1.3 GW) gas power with CO_2 removal (i.e., the combustion is practically CO_2 neutral) can be developed in Norway. This amount is associated with the oil field Grane where the Norwegian company Hydro is considering replacing natural gas with CO_2 for enhanced oil recovery. The potential to utilize natural gas condensing (combined cycle) power plants is assumed to be unlimited in all four countries except Finland, where there is a 4.5 GW limit. The cost of such plants in the model is the same in all four countries, except for the gas price. Natural gas in Norway is assumed to be 0.1 SEK/Sm^3 cheaper than in the other countries.

No major restrictions are set on new natural gas networks. Supply of natural gas in one country is not connected to the corresponding supply in one of the other countries. Thus, to the model it makes no difference if new transmission capacity for, e.g., the Swedish gas market is guided by a new pipeline from the North Sea to Gothenburg or directly from Russia.

[1] In the scenario "Steady Course" of the Norwegian Energy Commission it was assumed that approx. 10 TWh of the total new potential (so-called "Category 2" projects) could not be developed for environmental protection reasons.

Table 1
Fuel price projections for the years 2000 and 2030. [a]

Fuel	2000	2030
Coal	45	48
Heavy fuel oil	70	100
Light fuel oil	100	130
Natural gas	70	100
Bio fuels	100–150	100–150
Peat	100 (Swe), 75 (Fin)	100 (Swe), 75 (Fin)

[a] All prices in Swedish crowns (SEK) per MWh. 1 USD equals approximately 8 SEK. Fuel prices for 2010 and 2020 are calculated by interpolation.

Assumptions regarding fuel costs (excluding taxes) are found in table 1. The price of oil is assumed to increase gradually from approximately 18 USD per barrel in the year 2000 to 25 USD per barrel in 2030. This is in accordance with estimates from IEA (World Energy Outlook, 1998). Natural gas prices are assumed to equal heavy fuel oil prices. In the case of bio fuel the model contains a simplified supply curve with costs divided into a number of classes, where each class contains a limited amount of bio fuel. The costs for each class are constant over time. Bio fuel in the cheapest class costs approximately 100 SEK/MWh and the most expensive roughly 200 SEK/MWh.

The prices in table 1 represent the lowest fuel costs in the model, i.e., those prices are only valid for large-scale users like power plants. Depending on user category, transport and distribution costs are added (still excluding taxes) leading for example to a light fuel oil cost of 170 SEK/MWh for residential space heating in 2000.

No new electricity exchange capacity is permitted in the model. It is assumed that the present exchange capacity among the Nordic countries will be sufficient for many years to come. Pure market considerations would call for allowing the possibility for expanding connection capacity between the countries. However, we believe that it is unrealistic that any country will rely on imports to such a large extent that this will be necessary. No net import or export is considered with the rest of Europe except for an import of 6 TWh from Russia to Finland. Import at this level has been steady for several years and is expected to continue. This import is cheap and always used in the model runs. Electricity imports and exports resulting from the current and planned cable projects connecting the Nordic countries to the rest of Europe can in a first approach be expected to cancel each other out, as they will be used primarily to supply diurnal and seasonal peak power demands. Thus, the net energy flow over a year should be close to zero during normal conditions.

Since the database contains data originating from at least four different sources, one for each country, differences in national assumptions might lead to discrepancies when comparing the results for the countries. Examples on such assumptions are technological development for the

Table 2
CO_2-restricted scenario assumptions.

	No CO_2 trade	CO_2-emission-permits trade allowed
No electricity trade	**0/0**	**0/CO$_2$**
Electricity trade allowed	**Elec/0**	**Elec/CO$_2$**

same type of technology and potentials for end-use efficiency measures and energy conservation. Simple reasons for these differences are often hard to find and deserve a study in itself. In the database, technology data has been harmonized in the long run where this is considered reasonable and practical, i.e., differences are allowed during initial time periods but are equalized towards the end of the entire modeling period.

The transport sector is not considered in the study. Only a forecast regarding CO_2 emissions from the transport sector is included in order to estimate the level of total emissions.

5. Options for curbing CO_2 emissions

Four scenarios with CO_2 restrictions have been tested during this study. These are depicted in table 2 with their assigned notations that are used throughout the rest of this text. Trade of electricity and CO_2-emission permits are evaluated against scenarios where trade is not allowed. Combining the alternatives give in total four different situations. Additionally (not included in table 2) for comparison purposes, a business-as-usual scenario (designated BaU) is used. This scenario does not have any CO_2 restrictions whatsoever but permits net electricity trade. It reflects the present situation with no major changes in future energy policy issues. This scenario is used only to estimate the costs that are incurred on the energy system when CO_2 restrictions are imposed.

Scenario **0/0** is used as the "baseline" scenario in that respect that the three other scenarios with CO_2 restrictions are all compared to **0/0**. Thus, the estimated benefits of electricity trade and emission-permits trade and changes in demand-sector emissions are all expressed as differences between **0/0** and either **Elec/0**, **0/CO$_2$** or **Elec/CO$_2$**.

In scenarios **0/0** and **0/CO$_2$** net electricity trade among the Nordic countries is not allowed with exception for balance power trade, i.e., trade is allowed only for peak demands and regulating power purposes. These scenarios serve the purpose of creating a baseline for evaluating the effects of net electricity trade. In scenarios **Elec/0** and **Elec/CO$_2$** electricity trade between the four countries is allowed, but is limited by the capacity of existing exchange grids.

In two of the scenarios the Nordic countries are allowed to jointly meet their greenhouse-gas targets (scenarios **Elec/CO$_2$** and **0/CO$_2$**). This means that a total emission quota, equal to the sum of the four individual quotas, is applied to the entire Nordic energy system. Thereby,

Table 3
CO_2 emissions [Mt] in 1990 and imposed CO_2 restrictions for scenarios **0/0** through **Elec/CO$_2$**. For scenarios with CO_2 trade, the total level is applied.

	1990	2010	2020	2030
Denmark	60.2	47.6	44.5	41.5
Finland	53.8	53.8	51.1	48.4
Norway	35.5	35.9	34.1	32.3
Sweden	55.4	57.6	54.8	52.1
Total	204.9	194.9	184.5	174.3

restrictions on national levels are removed. We have assumed that no buying of quotas outside the Nordic countries is allowed. Co-operation with countries for instance in Eastern Europe and the former Soviet Union will probably reduce the marginal costs more and thereby most likely make emission-permits trade among the Nordic countries unprofitable. However, as we in this study are concerned with the interactions between electricity trade and (lack of) CO_2-trade among the Nordic countries, permits trade with other countries is not considered.

In all scenarios in table 2 it is assumed that the four Nordic countries fulfil their commitments (either jointly or separately) as agreed upon in Kyoto and the successive burden sharing negotiations among the EU member states. Accordingly, by 2010, emissions of the basket of six greenhouse gases are restricted to not increase more than $+1\%$ for Norway, $+4\%$ for Sweden, 0% for Finland and -21% for Denmark relative to 1990. As the Kyoto targets are considered to be far from sufficient for stabilizing the CO_2 concentration in the atmosphere, we assume a strengthening of 5%, relative to 1990, of the commitments per decade until 2030. An additional 5% per decade seems reasonable when taking into consideration that the agreed commitments until 2010 are of the same magnitude. The quotas are to be met by emissions reductions of CO_2 and five additional gases. However, the model database lacks information about measures to reduce emissions of the non-CO_2 GHGs. Therefore, the model optimization is solely done for CO_2. In other words, it is assumed that the national percentage reductions/increases are met uniformly among the GHGs, i.e., the percentages above are also valid for CO_2 individually. To neglect the option of curbing one of the six GHGs more than the others is of course a weakness in the methodology.

In table 3, CO_2-emission levels used in the model runs are shown. In 1990 the corrected emission level for Denmark is presented, while we use the actual emission levels for the other countries. Here, corrected levels refer to adjustments done to import or export of electricity. Thus, since electricity import was high in Denmark in 1990 (thereby replacing indigenous fossil-fuelled power) the corrected emissions level is higher than the actual level. Emission data is collected from [10].

Looking at the total Nordic CO_2 emissions in the chosen scenarios, they are compatible with a 5% reduction in 2010 compared to 1990, -10% in 2020 and -15% in 2030. It might be argued that a larger part of the reductions should be taken by the other greenhouse gases. If so, the marginal costs for CO_2 (equivalents) reductions will decrease.

6. Results

As was mentioned in section 1, the aim of this study is to answer three questions: What is roughly the size of the additional costs in the Nordic energy system when meeting the Kyoto protocol? What significance to these cost increases has electricity trade, emission-permits trade or a combined trade of both utilities? And finally, how is the burden sharing distributed among the different energy subsectors within the countries when changing the options for jointly curbing CO_2 emissions?

A first attempt to answer both the first and the second question can be found in figure 3. In this figure the increase in total discounted (to 1990) energy system cost is presented when fulfilling the Kyoto protocol with a further commitment of -10% between 2010 and 2030 (with or without electricity or emission-permits trade). The cost increases are naturally due to the imposed CO_2 restrictions. It is obvious that the increases in costs can be moderated, by allowing electricity and/or emission-permits trade. By looking at the height of the staples in figure 3, it can be concluded that the additional costs of meeting the Kyoto commitment can be reduced by approximately 10% by allowing electricity trade, 20% by allowing emission-permits trade and roughly 40% by allowing both trade options.

If the additional costs in figure 3 are related to the total discounted system cost for the BaU scenario, the magnitude of the numbers are quite modest. The additional costs for the most expensive option, i.e., no emission-permits or electricity trade (roughly 70 billion Swedish crowns in figure 3), is only about 2% of the total discounted system cost. However, it is crucial to bear in mind that this methodology only captures costs in the energy system. Nothing is revealed concerning effects in the rest of the macro economy. Since electricity costs rise under CO_2 constraints, prices are likely to follow. The shadow price on electricity is for instance approximately 20% higher in scenario **0/0** than in the BaU case in 2020. This might lead to welfare losses and income reductions (heavily or slightly) influencing the total cost budget.

In the text hereafter, the BaU scenario has fulfilled its purpose and is left behind. From now on, the discussions solely concern the four scenarios with CO_2 obligations according to the Kyoto protocol.

Figure 4 illustrates the value of electricity trade, emission-permits trade and a combined trade of both utilities in monetary terms (1 US$ = 8 SEK) under Kyoto obligations expressed as discounted system cost reductions compared to scenario **0/0** where no trade is allowed. Thus, this figure yields the same information as was given by the dotted staples in figure 3.

Figure 4 reveals that the cost reductions at hand when allowing free electricity trade and tradable emission permits under CO_2 constraints, is roughly 27 Billion Swedish Crowns. For comparison, it can be noted that the gross domestic product in Sweden 1996 was approximately 2000 Billion Swedish Crowns and in Norway 1300 Billion Swedish Crowns. Thus, in relation to other economic key figures and the total energy system cost, as was illustrated earlier, the additional costs of meeting the Kyoto target and beyond are fairly small for the Nordic countries.

According to figure 4, tradable CO_2 permits lead to larger cost reductions than electricity trade. If both utilities are tradable the gain is even larger than the sum of cost reductions for only electricity trade and only emission-permits trade. In figure 4 the sum of the separate values is indicated with a dotted line in the rightmost staple. Thus, an amplifying effect can be observed where trade of CO_2 permits and electricity interact. This should not come as a complete surprise. National CO_2 quotas prevent electricity trade, because they increase exporters' abatement costs. Similarly, free electricity trade increases the need for CO_2 trade, when one country is exporting electricity to the others (and when the production is based on fossil resources). Alternatively expressed, the amplifying effect can be explained in terms of trade value. In this case, the full potential value of making one utility tradable is not achieved unless the other utility is made tradable as well.

Figure 5 shows the changes in system costs for each of the four Nordic countries. In all transitions from scenario **0/0**, Swedish system costs are reduced, even if the reductions are small in scenario **0/CO_2**. This is mainly a result from the nuclear phase-out. In scenario **0/CO_2**, Norway experiences the largest share by far of the cost reduction. Trading CO_2 permits is highly attractive for the Norwegian industry, which can be seen in figures further on.

In all cases, Finland and above all Denmark experience increased costs when leaving the "non-cooperative" scenario **0/0**. Thus, in order to make common action attractive for all parties, Sweden and Norway have to compensate Denmark and Finland for their increased costs. This can for instance be accomplished directly through a combined emissions' and electricity market place where prices for these utilities are set. An indication of the magnitude of these market equilibrium prices for power and emission permits can be obtained by studying the shadow price (defined as the system's willingness to pay for an additional unit) on power production and CO_2 abatement yielded in the modeling results. For instance is the shadow price in 2020 on power production approximately 320 SEK/MWh electricity under the **0/0** scenario and 290 SEK/MWh electricity under the **Elec/CO_2** scenario. The corresponding shadow price for the same time period on CO_2 abatement is approximately 220 SEK/metric ton when electricity trade as well as emission-permits trade is allowed. Under **Elec/0** assumptions, the shadow price ranges from 50 SEK/metric ton to 620 SEK/ton with the lowest in Denmark and the highest in Norway. The shadow prices on CO_2 should be interpreted as additional to existing CO_2 taxes, since these

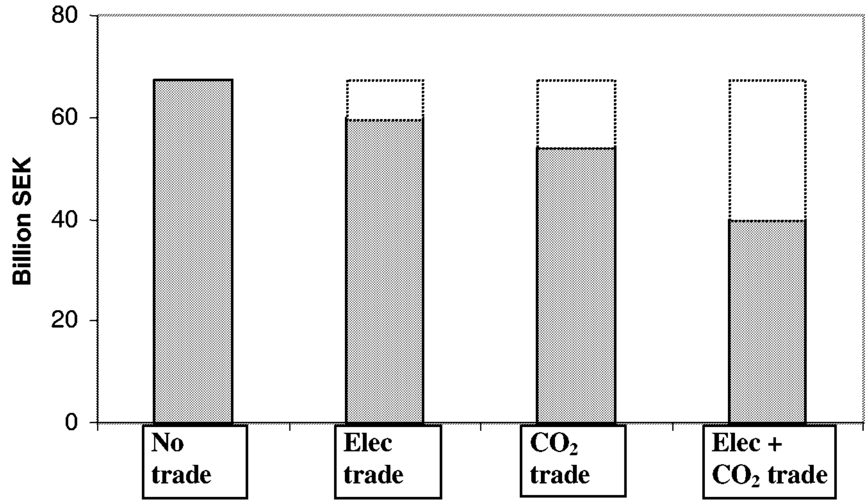

Figure 3. The total discounted energy system cost increases relative the total BaU energy system cost for four ways of meeting the Kyoto protocol. The dotted staples indicate the cost decreases due to trade, i.e., the value of trade.

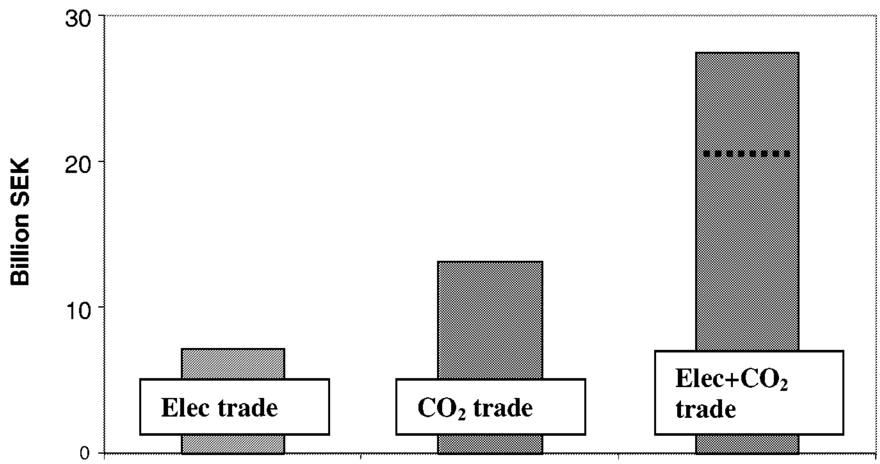

Figure 4. Reductions in total discounted (1990) system costs for the entire Nordic energy system when comparing scenario **0/0** (no trade) with scenarios **Elec/0** (Elec trade), **0/CO$_2$** (CO_2 trade) and **Elec/CO$_2$** (Elec + CO_2 trade).

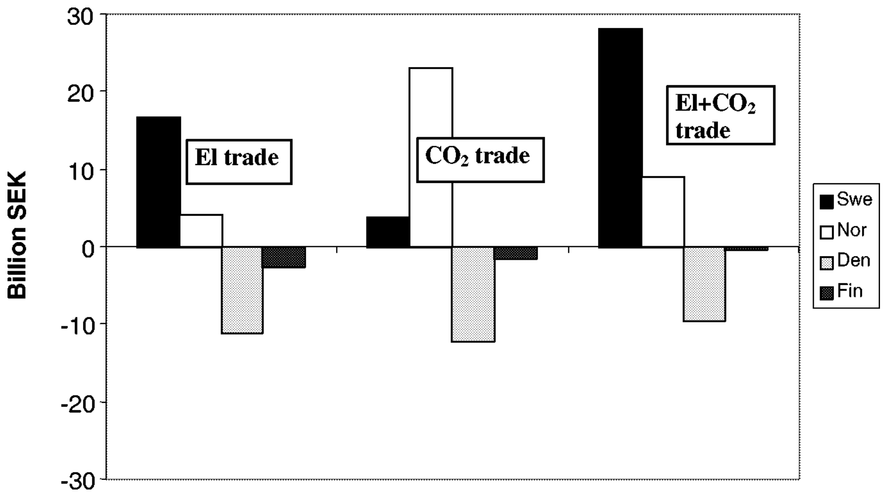

Figure 5. Reductions in total discounted (1990) system costs for each country when comparing scenario **0/0** (no trade) with scenarios **Elec/0** (El trade), **0/CO$_2$** (CO_2 trade) and **Elec/CO$_2$** (El + CO_2 trade).

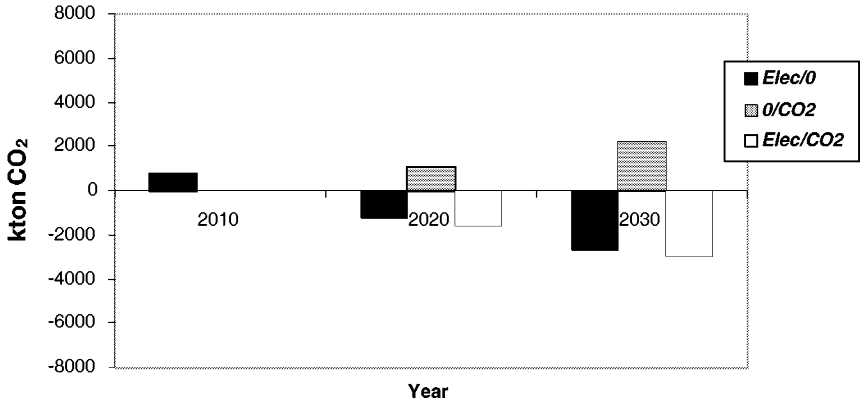

Figure 6. Separate power production sector in Sweden.

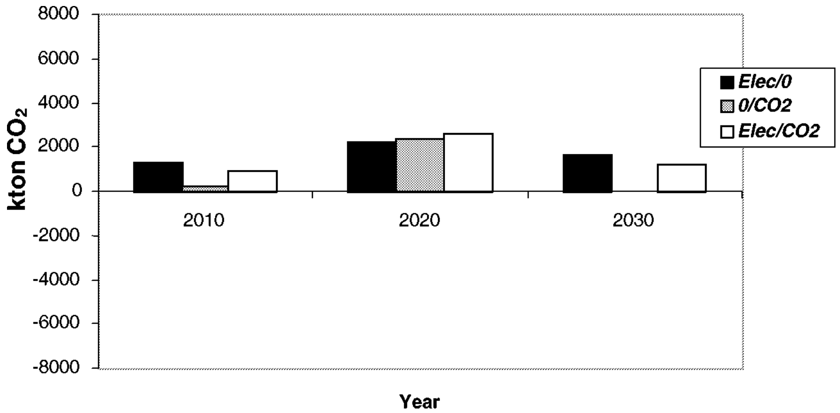

Figure 7. Industrial sector in Sweden.

are included in the model. Thus, the actual difference between Denmark and Norway is not that large because existing energy/CO_2 taxes generally are higher in Denmark than in Norway.

Although the shadow prices discussed above might be used for estimating the monetary net flow between countries, this study is restricted to a cost analysis of trading power and emission permits among the Nordic countries. No conclusions regarding the size of incomes from trade and, therefore, the net gains for each country are therefore made.

Now focusing on question number three in the introduction, the distribution of changes in CO_2 emissions among four sectors for scenarios **Elec/0**, **0/CO_2** and **Elec/CO_2** compared to **0/0** have been analyzed. The sectors are large-scale public power production units (*Power*), district heat and combined heat and power production units (*DH + CHP*), residential, commercial, agricultural (*Res&Comm*) and the industrial end sector (*Ind*). Industrial CHP is within the industrial sector, although these plants might serve the public with power. Sectors where the largest CO_2 emission changes take place when moving from scenario **0/0** to one of the others are presented in figures 6–11. In other words, these are the sectors which might act as active agents in an emission-permits market, i.e., for scenarios **0/CO_2** and partly **Elec/CO_2**. Positive numbers in the diagrams indicate incentives to *buy* permits (i.e., it is the difference between emissions in either **Elec/CO_2**, **0/CO_2** or **Elec/CO_2** and emissions in **0/0**) while negative numbers indicate incentives to *sell* permits comparing to the no-trade scenario.

Figure 6 presents the Swedish power production sector (only electricity production). Today, this sector is practically CO_2-emissions free (hydro and nuclear) but in the long run natural gas condensing as well as advanced coal firing (e.g., IGCC) plants might be economically realistic alternatives. This sector acts as a net buyer of emission permits. The same is not valid for the Swedish CHP sub sector for instance, where the use of bio fuels is dominating. Hence, there are reduced possibilities for this sector to be active on an emission permits market. However, with electricity trade the emissions in the power sector are reduced compared to **0/0** since Sweden can rely on imported electricty to a fairly large extent.

The industrial sector (including industrial CHP) in Sweden is shown in figure 7. Here, the trends are increasing CO_2 emissions for all scenarios.

The public power production sector in Finland is shown in figure 8. Since coal plays a major role in this sub-sector, it is obvious that CO_2 reductions are cost efficient when allowing emission-permits trade. Electricity trade helps in

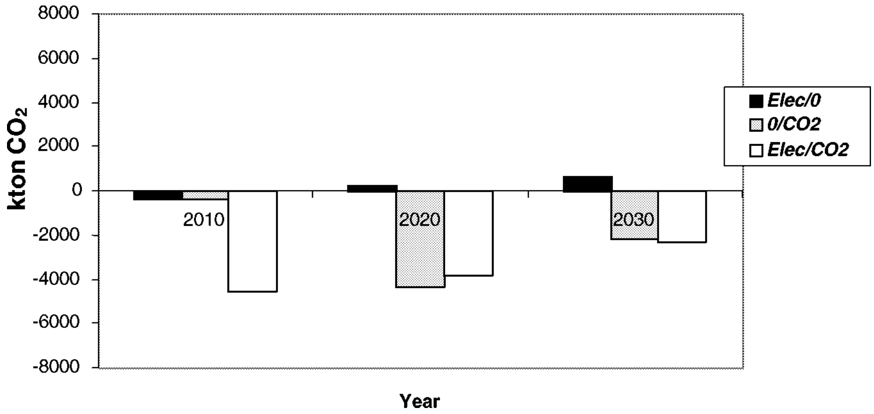

Figure 8. Separate electricity production sector in Finland.

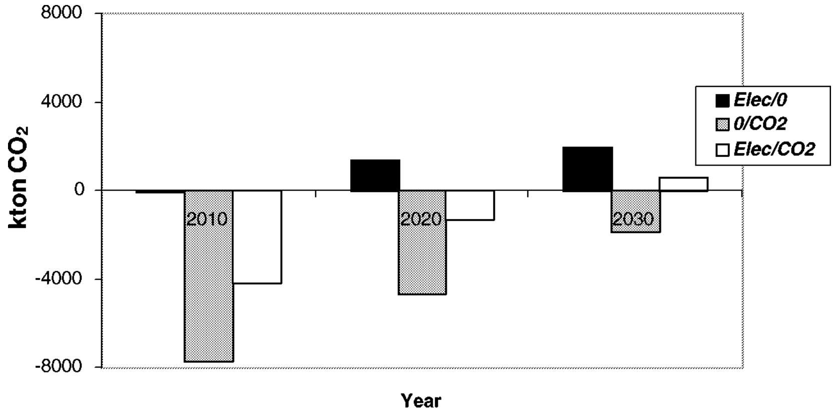

Figure 9. District heat and combined power and heat production sector in Denmark.

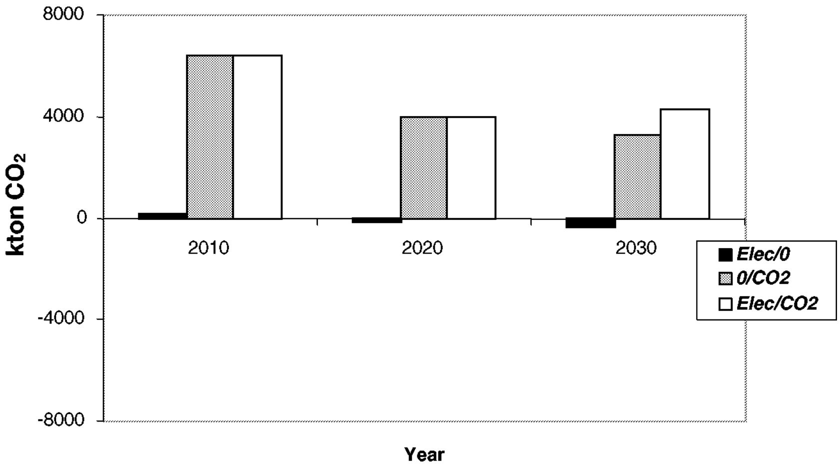

Figure 10. Industrial sector in Norway.

keeping the activity down, since imported (mainly hydro based) electricity is cheaper.

Correspondingly, the Danish DH + CHP sector in figure 9, acts as a seller of permits because of the pronounced reliance on fossil fuel. If only electricity trade is allowed, emissions will increase because of electricity export.

It can be noted that the separate-power sub sector in Denmark in the long run is being dominated by wind power and only to a minor extent natural gas and advanced coal condensing plants. Thermal power production in Denmark will most likely almost exclusively occur in the public CHP sub sector.

Figure 10 presents the industrial sector in Norway. The results indicate high incentives for buying emission permits. Thereby conversion from electricity use to fossil fuels occurs. This “releases” power for export.

The same is valid for the residential, commercial and agricultural sub sector in Norway (figure 11). Increased

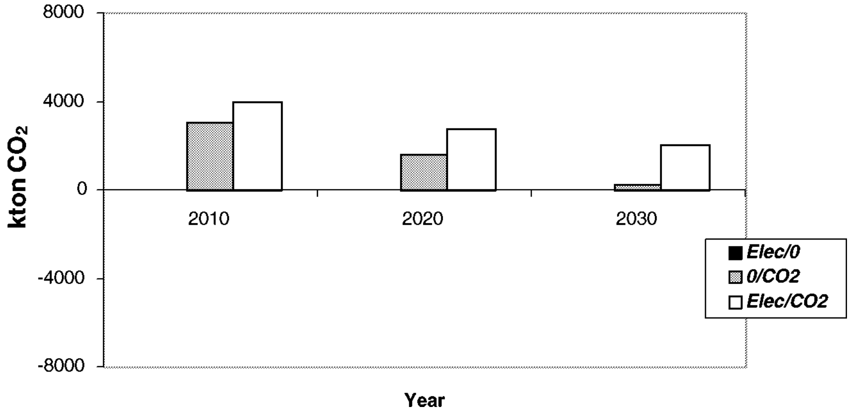

Figure 11. Residential and commercial sector in Norway.

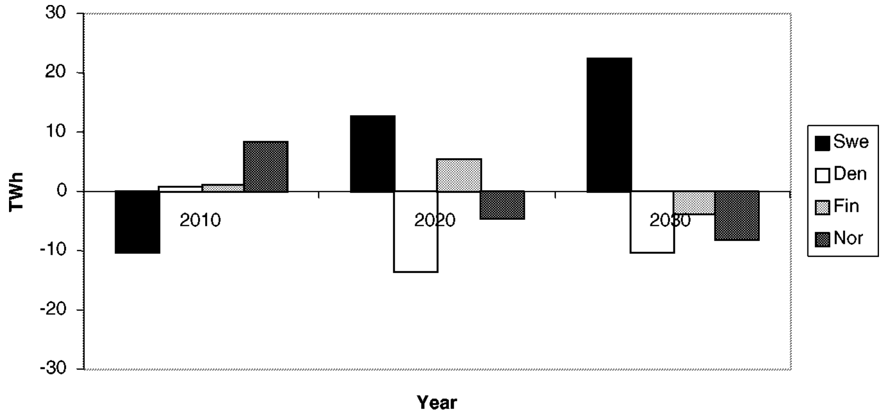

Figure 12. Net electricity trade among the Nordic countries when only electricity trade is allowed. A positive number indicates net import.

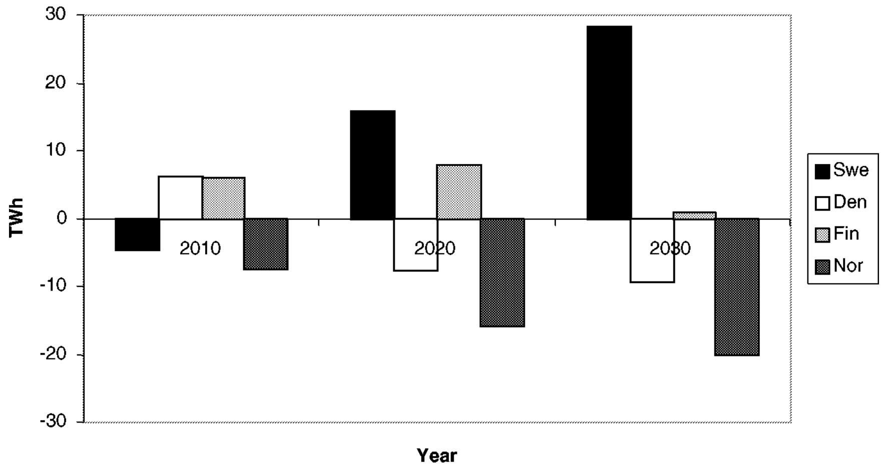

Figure 13. Net electricity trade among the Nordic countries when both electricity and emission permits trade is allowed. A positive number indicates net import.

use of light fuel oil and kerosene and reduced reliance on electricity compared to scenario **0/0** lead to increased CO_2 emissions. Taxes are lower for light fuel oil in Norway than in Denmark and in Sweden where the corresponding effect is not observed. However, if only electricity trade is allowed no electricity substitution occurs.

Figures 12 and 13 illustrate the net electricity trade among the four Nordic countries in scenarios **Elec/0** and **Elec/CO_2**. Positive numbers indicate net import in TWh to a specific country, while negative numbers reveal net electricity export.

From figures 12 and 13 it can be concluded that emission-permits trade boosts the Norwegian electricity export and the Swedish net electricity import. Denmark acts as electricity exporter during practically all circumstances. This is mainly due to the fact that it is cost efficient to use natural gas fired combined cycles with a high power-to-heat ratio for supplying Danish district heat under CO_2 restrictions. Thereby, the electricity production exceeds (in combination with a high reliance on wind power) the domestic demand leading to a substantial export. This in contrast to countries as Sweden and Finland where it is more favorable to utilize their vast bio mass resources in CHP units with low power-to-heat ratios. Another reason for natural gas CHP being more used in Denmark is lower CO_2 taxes on heat production than in for instance Sweden. Finland has to satisfy its high power demand forecasts partly with imported electricity.

7. Discussion

Naturally, the results are sensitive to different assumptions, some of which are rather uncertain. The vast amount of input data and assumptions concerning future behavior in the model represent one out of many possible sets of assumptions and input data sets. Assumptions and factors that heavily influence the model results include for instance fuel prices, the phase-out procedure of Swedish nuclear power (how and when) and presumptions concerning tightened emission targets after 2010. The discrepancies between data describing the same energy activity, but for different countries has been discussed in section 4. This might lead to the fact that for example potentials regarding energy savings and efficiency measures are overestimated for some countries while they are underestimated for others when they are compared. Countries with "optimistic" potentials will undoubtedly meet their CO_2 restrictions with less effort than countries whose potentials are relatively smaller, this being true or not.

Many experts question the nuclear phase-out in Sweden (see for instance [11]), particularly in combination with CO_2 emission-reduction targets. Nevertheless, to reflect current government policy we have chosen to gradually phase out the Swedish nuclear power in the scenarios. Allowing new nuclear capacity to replace existing units when they are decommissioned in Sweden would of course change the results. Dependence on imported electricity would thereby be reduced. The fact that nuclear power might be economically feasible under CO_2 constraints is shown for the case of Finland, where new nuclear units replace old capacity in all four scenarios. This is not generally the case if the CO_2 constraints are removed. We have also anticipated that one third of the total Norwegian new hydropower potential cannot be used, for environmental protection reasons. We assume that wind power will experience a pronounced cost reduction. This, in combination with large government subsidies until 2010 make way for a large-scale introduction of wind power. Further on, the assumptions concerning the possibilities to develop almost CO_2-free natural gas power (as in the case of Norway) might be optimistic. It should also be noted that the role of the Finnish energy-intensive industry as an actor in a possible emission-permits market most likely is somewhat underestimated. This is due to the fact that the industrial fuel end use in Finland is described by exogenous demand forecasts, implying that no endogenous fuel switching is possible. This modeling weakness does not apply to the industrial energy conversion sector, i.e., industrial back-pressure.

It can also be discussed whether it is reasonable to include existing taxes in a study like this. It might be argued that joint implementation requires harmonized taxes among the countries for reasons of fairness. However, we have chosen not to speculate in what future taxes and subsidies might look like. Instead, the starting-point for this study has been the tax system of today which is used throughout the modeling period. Model runs without any taxes or subsidies whatsoever under the scenario assumptions used throughout this work show that the conclusions and resulting trends basically are the same as what has been presented in this study.

There are also some shortcomings with the MARKAL model used. The demand for energy services is for example static, i.e., independent of energy prices. Thus, the only response to energy service cost increase in the model might be to use energy conservation or efficiency measures where this is favorable. To reduce the demand for the energy service in itself is not possible. General equilibrium models would prescribe a relationship between demand and prices. The deviation would be largest in energy intensive branches. Possible close down of factories is also dependent on measures implemented in other countries.

8. Conclusion

Some countries may be able to produce electricity cheaply but be restricted in their options for decreasing CO_2 emissions. Similarly, some countries may have favorable options for reducing CO_2 emissions, but expensive options for electricity production. The opportunities for harnessing the potential options of CO_2-emissions' reductions and electricity production are greater if both CO_2 emission permits and electricity can be traded freely.

To summarize and answer the three questions posed in the introduction, the following conclusions can be drawn:

- Compared to the total discounted energy system cost, the additional discounted cost of fulfilling the Kyoto protocol, is low. However, effects outside the energy system have not been evaluated.
- Under CO_2 constraints, the value (when looking at differences in total discounted system costs) of combined electricity and emission-permits trade can exceed the sum of the separate values of electricity trade and emission-permits trade. The value of emission-permits trade is somewhat larger than the corresponding value for electricity trade.
- Generally, under CO_2 constraints, Finland and above all Sweden will import electricity in the long run where

this is possible. Norway and Denmark are net exporters. Emission-permits trade boosts Norwegian electricity export and Swedish electricity import.

– The Swedish and Norwegian industry have pronounced incentives for buying emission permits. Sellers of these permits are mainly the Danish DH + CHP and the Finnish power producing sectors.

Acknowledgements

We would like to thank Antti Lehtilä at VTT in Finland, Poul Erik Grohnheit at Risø National Laboratory in Denmark and Thomas Krogh at Institute for Energy Technology in Norway, for supplying data for the Danish and Finnish energy systems. Valuable comments made by Håkan Sköldberg and Bo Rydén at Profu and Deborah Cornland at Chalmers/Stockholm Environment Institute have also been appreciated.

This work has been financed by the Norwegian Research Council – The SAMRAM Program, the Swedish National Energy Administration, the Swedish Power Association, the Swedish Gas Association, the Swedish District Heating Association and the Norwegian Electricity Association.

References

[1] FCCC, Report of the conference of the parties on its third session, held at Kyoto from 1 to 11 December 1997, FCCC/CP/1997/7/Add.1.
[2] Bahn et al., Advanced mathematical programming modeling to assess the benefits from international CO_2 abatement cooperation, Environmental Modeling and Assessment 3 (1998) 107.
[3] Larsson, Grohnheit and Unander, Common action and electricity trade in Northern Europe, International Transactions in Operational Research 5(1) (1998).
[4] NORDEL, Årsberättelse 1997 (in Nordic languages).
[5] Dansk Elforsyning Statistik 1996, Danske Elvaerkers Forening (in Danish).
[6] Energy Statistics 1996, Statistics Finland.
[7] W. Marcuse et al., A dynamic time dependant model for the analysis of alternate energy policies, in: *Operational Research '75*, ed. K.B. Haley (North Holland, Amsterdam, 1976) pp. 647–667.
[8] Fishbone and Abilock, MARKAL – A linear programming model for energy system analysis – technical description of the BNL version, *Energy Research*, Vol. 5 (1981).
[9] P. Andersen and P. Fuglsang, Vurdering av udviklingsforløb for vindkraftteknologien, RISØ-R-829(DA) (Forskningscenter RISØ, Roskilde, 1996) (in Danish).
[10] IPCC, 2nd National Communications for Norway, Sweden, Denmark and Finland.
[11] W.D. Nordhaus, The Swedish Dilemma – Nuclear energy vs. the Environment, SNS No 74 Occasional Paper (Nov-95).