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Co-existence of electricity, TEP, and TGC markets in the Baltic Sea Region

Magnus Hindsberger, Malene Hein Nybroe, Hans F. Ravn*, Rune Schmidt

Elkraft System, Lautruphøj 7, DK-2750 Ballerup, Denmark

Abstract

This paper analyses the application of two policy instruments, tradable emission permits (TEPs) and tradable green certificates (TGCs) to the electricity sector in an international context. The paper contains an explicit modelling at two levels of abstraction, one suitable for defining and analysing basic functionalities and one suitable for numerical analysis in relation to countries in the Baltic Sea Region. Emphasis is on estimating implications in quantitative terms for countries in the Baltic Sea Region in 2010 when the TEP market in the analysis extends to four Nordic countries (Denmark, Finland, Norway, Sweden), and the TGC market extends to North European EU countries (Denmark, Finland, Sweden, Germany). The study concludes that within the range of goals stipulated in the EU draft directive (23.6% renewable energy) and the Kyoto targets for emissions, the following prices are affected significantly: from –2 to +10 Euro/MWh for electricity spot prices, TGC prices up to 50 Euro/MWh, TEP prices up to 18 Euro/t CO_2 and up to +15 Euro/MWh on the consumer cost. It is shown that such price changes have important consequences for the production and investment patterns in the electricity sector, and the resulting patterns will be clearly different according to the specific numerical targets for the two goals. An immediate consequence is increased pressure on transmission lines. Further, the introduction of TEP and TGC markets will imply a restructuring of the electricity sector, e.g. (depending on the specific combination of targets) by a significant increase in wind power capacities. However, this will have to be counterbalanced by access to production technologies that have fast regulation properties and/or that may maintain voltage stability. However, the price signals of TGCs (and to some extent also TEPs) that will enhance wind power investments will simultaneously hamper investments in technologies that are a precondition for extensive use of wind power technologies.

1. Introduction

The reduction in greenhouse gas emissions is an increasingly important issue in the energy and environment policies of the European Union, accession countries and other industrialised countries. The Kyoto Protocol and the related emission targets set the agenda for the future energy policy in the region (European Commission, 2001). The Kyoto Protocol introduced the concept of flexible mechanisms, and agreements about the rules for these mechanisms have recently been discussed at the seventh session of the Conference of the Parties in Marrakesh in 2001. With the decisions in Marrakesh, the road has been paved for emission trading, joint implementation and clean development mechanisms.

Also promotion of renewable energy is high on the agenda in Europe (European Commission, 2000a). Renewable energy can contribute to reducing greenhouse gas emissions, but it also has other assets. In its green book on security of supply the EU points at the positive effect of renewables on diversification of energy supply (European Commission, 2000b). In the long run, renewable energy may be a better answer to the climate problem and to a sustainable energy system than traditional energy transformation based on fossil fuels. In the short run, renewables cannot compete with other greenhouse gas reduction options, and this has lead to the development of separate promotion schemes for renewables. One of the schemes that are being discussed internationally is a market for renewable energy certificates.

The questions of emission reduction and renewable energy promotion are on the agenda in other contexts as well. Thus, the Nordic Ministers of Energy have recently emphasised the possibilities of using the Baltic Sea Region as a testing ground for joint implementation. They have further pointed at the possibilities of emission

*Corresponding author. Tel.: +45-4487-3618; fax: +45-4487-3210.
E-mail address: hrv@elkraft.dk (H.F. Ravn).

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trading between the Nordic countries and a Nordic market for renewable energy certificates and agreed to support the development of a sustainable electricity market around the Baltic Sea. This may be seen as a commitment to developing a testing ground for the Kyoto mechanisms in the Baltic Sea Region (Nordic Council of Ministers, 2001). These initiatives are sustained by national investigations and proposals, e.g. Energistyrelsen (1999) in Denmark and Miljödepartementet (2001) and Näringsdepartementet (2001) in Sweden.

The introduction of systems for tradable emission permits (TEPs) or tradable green certificates (TGCs) are immediate suggestions for instruments of international cooperation on these issues. The introduction of TEPs and TGCs will create two new interdependent products, and they will in turn interact with the electricity market. In the short run, this will affect emissions through changes in electricity production, consumption and trade. In the longer run, the production capacities for the various types of electricity production capacities will be affected, and in particular favour renewables to the extent warranted by the price signals.

As the initiatives in the Baltic Sea Region illustrate, international initiatives and cooperation on emission reduction, introduction of renewables, and the existence and enhancement of electricity markets need not have the same geographical coverage. In particular, cooperation may involve EU and well as non-EU countries. Also with respect to the constitution of the energy systems and the economic conditions, the cooperating countries may differ vastly.

Therefore a number of unanswered questions remain in relation to the specific architecture and to economic efficiency issues. In part this is because a number of practical implementation issues must be settled. However, it is also because there is an intrinsic interplay between the introduction of TEP and TGC systems and key evaluation parameters. Relevant evaluation parameters are economic efficiency, consumer prices, producer profits and distribution of costs and benefits between the countries participating in such international cooperation.

This is demonstrated in a number of papers dealing with the questions concerning two instruments (TEP and TGC) and/or two or more countries. Thus, in the treatment of the Danish green certificate system, Amundsen and Mortensen (2000) demonstrate among other things that the effects of an increase in the percentage requirement of green electricity's share of the total electricity consumption are most inconclusive. Morthorst (2001, 2002) deals with TEPs and TGCs in an international context and concludes among other things that the application of the two instruments must be coordinated in order for the benefits to be distributed internationally in proportion to the level of ambition of the national targets. Jensen and Skytte (2002a, b) also demonstrate that there is no simple relationship between targets for emission and renewables and consumers' cost of electricity.

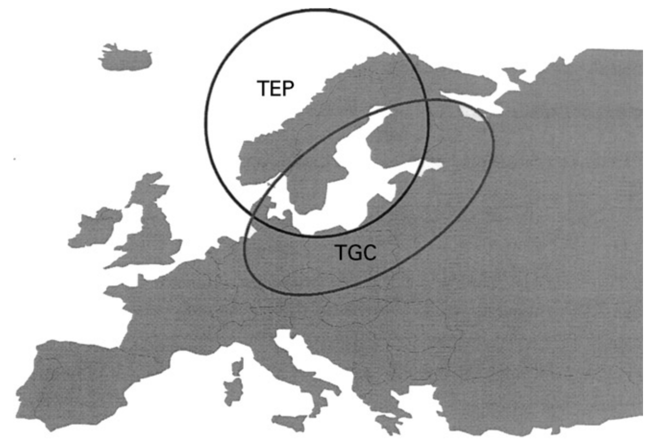

Fig. 1. International markets in addition to the electricity market.

A common lesson from these theoretical investigations is therefore that some of the consequences of introducing TEP and TGC systems in an international context cannot be assessed on theoretical grounds alone.

On this background the purpose of the present study is to apply an empirical model to investigate some of the consequences of introducing such systems. In particular, trading of TEP, TGC and electricity will be analysed in a situation where the corresponding markets do not necessarily coincide, i.e. in the countries near the Baltic Sea.

The paper presents the theoretical framework and modelling in Section 2. A numerical model covering the Baltic Sea Region is established in Section 3. The spot market for electricity extends to all countries considered (subject to transmission constraints). The TEP market consists in the present analysis of four Nordic countries. The TGC market here consists of the North European EU countries shown in Fig. 1. Section 4 presents the results of the calculations. The results include the various prices (TEP, TGC, electricity spot price, consumer price and consumers' cost) relative to introducing emission trading and trade of renewable energy certificates in this region. The consequences for profits for owners of the various types of production technology are analysed. Further, implications for the physical constitution of the electricity sector, including investments in new technologies and transmission between countries, are investigated. Section 5 points to the perspectives of the analysis.

2. Theoretical framework and modelling

The international dimension in focus is represented by the definition of a number of countries and the exchange of TEPs, TGCs and electricity between them. Therefore an initial description will be given as motivation for the formulation of an adequate mathematical model. The description is given at a fairly abstract level, and a number of details included in the model used for the numerical analysis are not commented on here, see Section 3.

In the Kyoto Protocol, the emission limitations are specified at the level of countries. However, national emission limits are not strict and may be violated provided the surplus amount is counterbalanced by a similar reduction in another country, i.e. the flexible mechanism. An international system of TEP administration aims at ensuring that the sum of national emissions does not violate the sum of national emission limits.

This analysis assumes that a share of the national limit of each country has been allocated to the electricity sector. At present, this assumption is unrealistic, although some countries (e.g. Denmark) have initially implemented such sector emission limits. International exchange of TEPs is furthermore assumed to be permitted between the electricity sectors of the participating countries. The electricity producers in the countries may only cause emissions if they are associated with the acquisition of a corresponding amount of TEPs; the total amount of TEPs corresponds to the total emission which allowed the electricity sector in the countries in the emission bubble. In each country, the TEPs corresponding to the national quota allocated to the electricity sector may be given to the producers (grand fathering) or bought from the state.

The system of TGCs originates from the requirements in some of the countries that a certain share of electricity must come from renewable energy. This binds the consumers to match the purchase of electricity with the purchase of a proportional amount of TGCs. This involves a system that certifies green electricity, it involves the issuing of a number of TGCs to the production unit owners proportional to the amount of electricity produced, and it involves a market for the exchange of TGCs. The producers may sell the TGCs to the consumers. International exchange of TGCs may also take place if agreed between countries so that the TGCs bought by a consumer in one country may originate from the consumer's country or any other country in the TGC bubble. Observe that in this analysis it is assumed that CO_2-reduction due to increased renewable energy production is handled exclusively through the TEP system and not as a part of TGCs.

Finally, the international exchange also involves electricity. The physical basis is that the electricity production systems in the various countries are connected by an electricity transmission system with given characteristics (capacities) for the individual transmission lines. The supply systems in the various countries have technologies based on renewable energy sources (producing green electricity and associated TGCs) as well as other technologies (e.g. based on fossil or nuclear fuels—some of them emitting greenhouse gases). In the following, they are referred to as renewable and traditional technologies, respectively. This classification is a matter of definition. Thus, examples of traditional technologies without emission are nuclear and (depending on adopted definition) large-scale hydro. Examples of renewable technologies with physical emission are those based on incineration. The market side of electricity consists of an international spot market where demand and supply are cleared by the spot price in each country. The two types of technologies sell their electricity on the same spot market. International transmission is possible on market conditions. Electricity prices will thus be the same within two countries connected by a transmission line if the transmission capacity is sufficiently large. If the transmitted quantity is equal to the transmission capacity, prices may differ, with the import country having the higher price.

Thus, the theoretical set-up contains three distinct international markets: the spot market for electricity, the TEP market in relation to emissions, and the TGC market in relation to renewable energy. As described, the markets need not have the same geographical extension.

The above elements are integrated into a model in the context of maximising the sum of consumers' and producers' surplus, i.e. it involves an integrated demand and supply system. The specifics of the system are the incorporation of environmental and energy constraints in an international context with trade possibilities. Thus, in addition to the basic constraints of physical nature, describing the supply and demand equations and the production units' technical characteristics, three sets of additional elements must be introduced. One element must express the possibility of international electricity trade within the technical possibilities of transmission. The second element must express that for the countries in a defined bubble, a minimum share of the electrical energy consumed must come from renewable sources, and that trade in TGCs may take place between those countries. The third element must express that each country in a defined bubble has imposed limits on the emission from the electricity sector, but that trade in TEPs may take place between those countries.

At the present level of specification, the ideas of the above model are believed to be close to the ideas behind the reasoning in Morthorst (2001, 2002), Jensen and Skytte (2002a, b) and Amundsen and Mortensen (2000). Thus, the verbal description of the various instruments and mechanisms in relation to TEPs and TGCs seem almost identical. The exception is Amundsen and Mortensen (2000), where minimum and maximum prices of TGCs, and a maximum price of TEPs are introduced. The quoted papers differ with respect to emphasis on international aspects; thus, the papers by Morthorst (2001, 2002) treat several countries in equal detail, the Amundsen and Mortensen (2000) paper treats one country but analyses import and export, while the papers by Jensen and Skytte (2002a, b) focus on one country. All the quoted papers assume a convex model in the sense of the model shown in Appendix A. The Amundsen and Mortensen (2000) and the Jensen and Skytte (2002a, b) papers contain explicit mathematical models, while the other papers rely on verbal and graphic reasoning.

In the appendix, a mathematical model is formulated for the above-mentioned framework. The model is formulated explicitly as a one period static model with possibilities of investment in new production technologies. The appendix also stipulates basic properties of the model. Basic assumptions for the derivation are that the market is assumed perfectly competitive. This permits the formulation as an optimisation problem and the derivation of prices. Prices are found as optimal Lagrange multiplier values so that the electricity prices observed on the spot market are identical to marginal production costs (short-term marginal costs if there is surplus capacity, long-term marginal costs if there is a shortage). The prices of TEPs and TGCs reflect marginal costs associated with the constraints on emission and renewable energy application, respectively. Further, convexity assumptions imply certain monotone properties of the prices. Trade in electricity is represented directly in the model. Trade in TEPs and TGCs is not represented directly. However, the quantities traded may be derived from the optimal solution as discussed in the appendix.

As outlined in the introduction, the motivation for the introduction of international markets for TEPs and TGCs is that this is a way of obtaining economic efficiency in the attainment of the goals of emission and renewable energy share. Thus, the more countries participating in a bubble, the higher the efficiency gain may be. The same observation applies to an international electricity market. This feature is well understood and may be formally derived from the model in the appendix, but it will not be analysed here.

As concerns the emission goal, the TEP price will increase if the permitted amount of emissions is decreased. The cost of buying TEPs on the international market will be internalised in the electricity price on the spot market. Thus, the higher the TEP price is, the higher the electricity spot price is.

However, with respect to the renewable energy goal the situation is reversed. Thus, if the share of renewable energy is increased, the electricity supply offered on the spot market increases. The assumption of low marginal production costs of renewable electricity implies that traditional electricity will be replaced by renewable electricity, and the spot price will decrease. The TGC price in turn will increase if the share of renewable energy is increased.

The model also permits the calculation of consumers' and producers' surplus, and thus the distributional effects of the introduction of goals for emission limitation and renewable electricity production. Finally, the model is dynamic in the sense that it identifies new investments, and hence a description of the changes of the physical side of the supply system is possible.

3. Numerical model and data

The above quite general understanding has been applied to an empirical analysis of countries close to the Baltic Sea. The numerical model to be used incorporates the empirical details that are not necessary for presentation of the general ideas and properties of the model in Section 2, but that are essential in order to reach conclusions of a quantitative nature.

The obvious shortcoming of the model in the appendix is the abstract formulation with functions that have not been explicitly specified (e.g. the demand function in country c is given as D^c, and the electricity production cost function for unit i is given as f_i) and therefore allow for a wide variety of instances. In a numerical model, the abstract functions must obviously be specified.

However, apart from this, the model in the appendix has a number of structural shortcomings. Some of them will tend to bias the quantitative results in the direction of underestimating prices. The most important ones relate to the representation of the electricity system. First, the time dimension (not explicitly indicated in the appendix) involves only one time period, which may then be interpreted to be 1 year. For electricity systems, many important features involve shorter time intervals reflecting in particular the variation on electricity demand over the day and year, and forced electricity production from wind turbines, etc. Secondly, relevant constraints on electricity production units link individual units together, e.g. requirements of reserve capacity; also the linkage to the heat demand side (through combined heat and power units) is omitted in the formulation. Thirdly, losses in distribution and transmission are not represented. Fourthly, countries are represented in the geographical dimension. However, in many applications the electricity system must be represented in more geographical detail. Other important aspects relate to the cost structure; in particular taxes and tariffs may influence the results significantly.

The numerical analysis was made using the Balmorel model and adapting it to the specific purpose. This model represents the principles of the appendix and permits specification of additional elements to overcome the structural shortcomings mentioned of the model mentioned in the appendix.

The Balmorel model was developed recently in cooperation between various organisations in the countries around the Baltic Sea (Ravn et al., 2001; Ravn, 2001). The model contains a specification of geographically distinct entities and covers (at least parts of) the countries around the Baltic Sea, and it also includes Norway. On the supply side, it describes possibilities and restrictions in relation to generation technologies and resources, transmission and distribution constraints and costs, and different national characteristics (costs, taxes, environmental policies, etc.). In the time dimension, the model covers the large perspective (up to 2030) with a subdivision of the year into a number of sub-periods. This number may be chosen according to the character of the analysis and the data available; for the present study, a division into four sub-periods was used.

The model has a specification of the electricity and combined heat and power (CHP) production system based on 10 different classes of technology (including thermal, condensing and backpressure types and renewable technologies based on wind, hydro and solar sources). The model permits specification of production and investment costs dependent on the year and the country. As regards production, both short-term marginal costs (fuel, operations and maintenance costs) and investment costs (long-term marginal costs) are represented. The physical constraints represented include generation possibilities of the different technologies according to, for example installed capacities and fuel availability. Also transmission and distribution constraints are satisfied along with balance between supply and demand, appropriately taking into account losses and limitations.

The model determines the following entities: Generation of electricity and heat distinguished by technology and fuel; consumption of electricity and heat; electricity transmission; emissions; investments in generation and transmission capacities; prices of electricity and heat. All these entities are specified with respect to time period within the year and geographical entity. The variables are determined to either maximise the sum of producers' and consumers' surplus or to minimise the costs in the supply system. Properties of the solution are: Equilibrium in each sub-period between the marginal cost of electricity of distinct regions taking into account transmission losses, storage possibilities, costs and constraints; equilibrium between short-term and long-term marginal generation costs in each geographical entity so that long-term marginal costs prevail in periods in which capacity is extended, and short-term marginal costs prevail in periods with surplus capacity.

For the purpose of the present study, the base version of the model structure was supplemented in order to represent the quota and trade mechanisms related to TEPs and TGCs. This was done in accordance with the ideas outlined in the appendix. Thus, the model captures the spirit of the driving mechanisms of the model. However, as described, a substantial additional amount of empirical information is represented in the empirical model. As an indication of the size of the model it can be mentioned that for the present analysis it contains approximately 90,000 equations and 100,000 variables.

The data for the model are based on a variety of sources. In relation to technologies, international data bases were used, including the Baltic 21-Energy study (Baltic 21, 1998). Concerning other information such as electricity and heat demand, transmission networks, and taxes, international sources were used, e.g. IEA energy balances. In addition to these open sources, the Balmorel project involved data collection by local participants in the countries around the Baltic Sea.

While the Balmorel model originally contains a quite detailed description of the electricity and CHP sector, it was found necessary to supplement it with respect to renewable energy, which is in particular focus here. This was done by adapting data from the Rebus project (Voogt et al., 2001) which provides insight into the effects of implementing targets for renewable electricity generation at EU member state level and the impact of introducing renewable burden-sharing systems within the EU, e.g. TGCs. As part of that project, a database was developed describing the costs and potentials for renewable electricity. Wind turbines, small hydro, solar, biomass/wood, solid agricultural wastes, solid industrial wastes, wave and tidal, geothermal, large hydro, biogas, municipal solid waste were included in the definition of renewable sources of electricity.

The model represents Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland and Sweden. These countries are linked in a common electricity market in the model. The renewable energy bubble consists of the EU countries (Denmark, Finland, Sweden, Germany), while the emission bubble consists of the Nordic countries (Denmark, Finland, Norway, Sweden). See Fig. 1.

The specification of goals for renewable electrical energy is based on the goal (23.6%) stated in an EU draft directive from 2000 (European Commission, 2000a) (see Voogt et al., 2001, p. 22). This is taken as the most ambitious renewable energy goal. The specification of goals for emission reduction is modified from the Kyoto targets (UNFCCC, 2001). Since only the electricity and CHP sector is modelled here, it has been assumed that the national quotas have been further distributed on sectors in proportions corresponding to the historical (1990) CO_2 emissions. For the emission bubble a 55.88 Mt CO_2 limit is used as the most ambitious goal. This corresponds to the allowed

Table 1
The different levels of required renewable energy share in EU and Nordic emission limits

Nordic CO_2 emission limit (in Mt)	EU renewable energy share of demand (in %)
100.6 (TEP0)	0.0 (TGC0)
89.4	4.7
78.2	9.4
67.1	14.2
55.9 (TEP1)	18.9
	23.6 (TGC1)

emission from the four Nordic countries included in the study.

Based on the most ambitious goals, 30 different cases consisting of combinations of emission and renewable energy goals were defined. These are made up of six different levels of the renewable energy target of the EU countries included combined with five different levels of the amount of permitted emission of the Nordic countries included. The corresponding levels are shown in Table 1. Note the identification of the four extreme cases TEP0-TGC0, TEP1-TGC0, TEP0-TGC1 and TEP1-TGC1.

The calculations are performed for the year 2010. Investment may be made in new production technology in relation to the capacities existing in 2000. As currency Euro 2000 has been used (denoted EUR00 in the following).

4. Simulation results

The presentation of the results of the model calculations includes prices, different producer type incentives for investments, new production technologies, electricity transmission between countries, and trade in TEPs and TGCs.

Graphic illustrations of prices are given in Figs. 2–5. Fig. 2 shows the average annual electricity spot price for Eastern Denmark. From the least ambitious case (high emission level and low renewable energy requirements, front left corner in the figure; cf. also TEP0-TGC0 in Table 1) a price of 21 EUR00/MWh is seen. Adding strong renewable energy requirements makes the price drop about 10% to 19 EUR00/MWh, while the price would grow by 50% to more than 31 EUR00/MWh if a strong limit were enforced on emission instead. If ambitious goals are adopted on both renewable energy and emission, the price will be approximately the same as without any goals. The relatively flat shape in the direction of increased renewable share is due to the already existing renewable energy production. This is also clearly visible in Fig. 3, which shows the calculated common EU prices of TGCs. A TGC price of

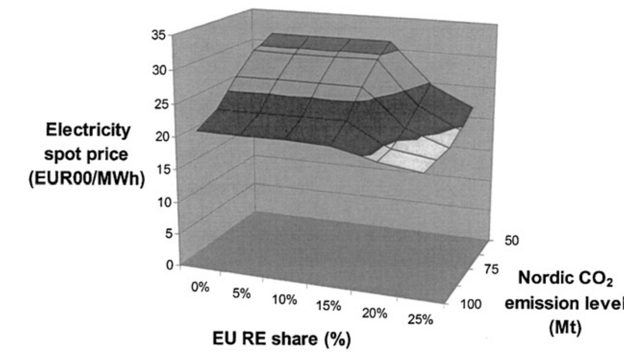

Fig. 2. The annual weighted average spot price in Eastern Denmark.

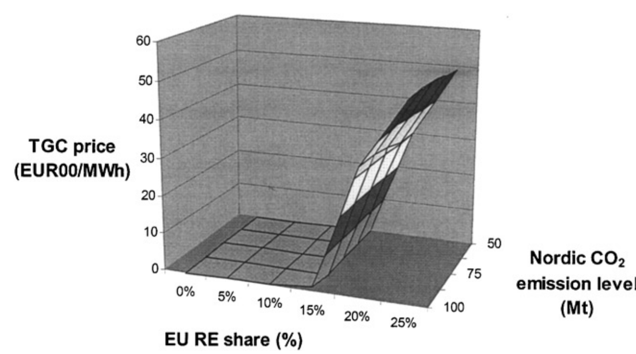

Fig. 3. The price of TGC in the EU countries.

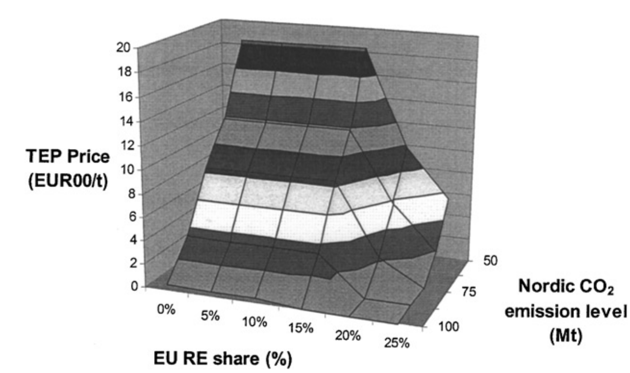

Fig. 4. The TEP price in the Nordic countries.

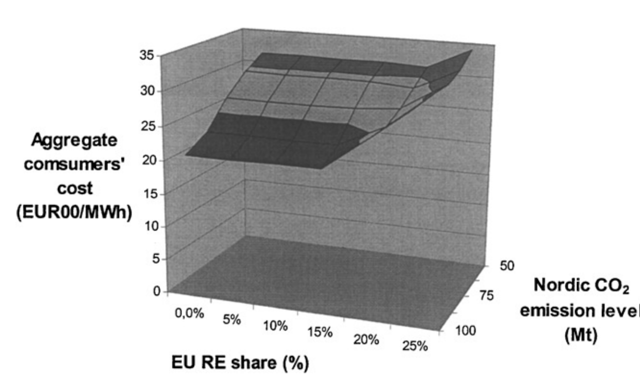

Fig. 5. The aggregate consumers' cost (weighted spot price + TGC) in Eastern Denmark.

Table 2
Annual weighted average spot prices 2010 (in EUR00/MWh)

	Denmark—E	Denmark—W	Estonia	Finland	Germany	Latvia	Lithuania	Norway	Poland	Sweden
TEP0-TGC0	21	21	27	19	31	29	32	21	20	21
TEP0-TGC1	19	18	27	15	23	29	32	17	20	17
TEP1-TGC0	31	30	27	29	32	29	32	26	20	27
TEP1-TGC1	22	21	27	19	23	29	32	21	20	20

50 EUR00/MWh can be seen corresponding to the EU draft directive on renewable energy. It is virtually independent of the emission constraints. Similarly, Fig. 4 shows the calculated common prices of TEPs in the Nordic countries. It can be seen that the price of the emission permits may rise to 18 EUR00/t CO_2 for the cases with strong emission quotas but only weak requirements of the renewable energy share of the electricity supply. As expected, the price drops as the renewable energy share is increased, and very sharply. Finally, Fig. 5 shows the aggregate consumers' cost of electricity in Eastern Denmark (i.e. the sum of the electricity spot price and the price of the TGCs, where the latter is weighted by the appropriate share). This corresponds to the consumers' marginal cost of using electricity assuming no taxes or distribution costs are added. As seen, the aggregate cost tends to increase with increasing TGCs and decreasing TEPs, up to almost 15 EUR00/MWh. Observations of the spot price and the aggregate consumers' cost for the other Nordic countries will look very similar to the ones for Eastern Denmark (Figs. 2 and 4), and the graphs are not given, spot prices for all countries are given in Table 2. Taking into account that the annual amount of electricity consumption in the Nordic countries is approximately 400 TWh, the indicated marginal price increase of 15 EURO/MWh will imply an increase in consumers' cost of electricity of up to 6 billion EURO. However, it should be noted that the spot price in Germany does not change significantly when the CO_2 allowance in the CO_2 bubble is changed. This is because Germany is outside the CO_2 bubble. If the transmission capacities were unlimited, the price would be the same everywhere due to the assumption of perfect market conditions. However, the German market is large in comparison with the transmission capacity linking Germany to other countries (capacities of approximately 120,000 and 2000 MW, respectively); transmission is discussed in further detail below. As seen, the theoretically derived results of monotone connections between quotas and prices (cf. the appendix) are confirmed. As a special point, note that for the aggregate consumers' cost, Fig. 5, there is no complete monotonicity. Thus, around 55 Mt CO_2 emission allowance and 18.9% renewable energy requirements the price drops slightly (hardly visible). The possibility of such non-monotone relationship is predicted and analysed in Jensen and Skytte (2002a, b). Though non-monotonic price relations are seen in the simulation results these are observed to be of minor relevance in the overall picture.

As concerns the producers' surplus, the picture is complicated. The surplus gained by the owner of a particular production unit depends on the cost of production (and for new investments also on investment costs) and on one or two prices in the TEP and TGC market. For production units based on renewable energy, the relevant prices are the spot price and the TGC price. For production units with emissions, the relevant prices are the spot price and the TEP price. For production units that have no emissions and do not qualify for a TGC (e.g. nuclear or large hydro), the relevant price is the spot price. Hence, the various types of production technology will be quite differently affected by the policy measures adopted. An illustration is given in Fig. 6, which refers to the situation in Sweden. The graph shows the variable production costs for different types of technology in two cases: no emission limitation (TEP0) and maximum emission limitation (TEP1). Since the cost of acquiring the necessary TEPs associated with production is internalised into the electricity production cost, the cost will increase for the production types that have emissions. The graph also shows the electricity spot price in Sweden in four extreme cases. As seen, the variations on the spot price imply that some of the technology types may change the situation from earning money to losing money. Heavy restrictions on emissions penalise the fossil-fuelled technologies significantly, and the associated increase in the spot price does not compensate for this. For non-emitting technologies (renewable and nuclear) the cost is not affected by emission limitations, but the income is. Thus, apart from the effect of the policy measures on the redistribution between producers and consumers, there is a substantial redistribution between the owners of the different types of technology.

The consequence of high profitability for an individual type of technology in a given country is that more capacity of this type will eventually be established. This effect is illustrated in Table 3 where the production in 2010 at units constructed between 2000 and 2010 is shown for three cases. It can be observed that only for

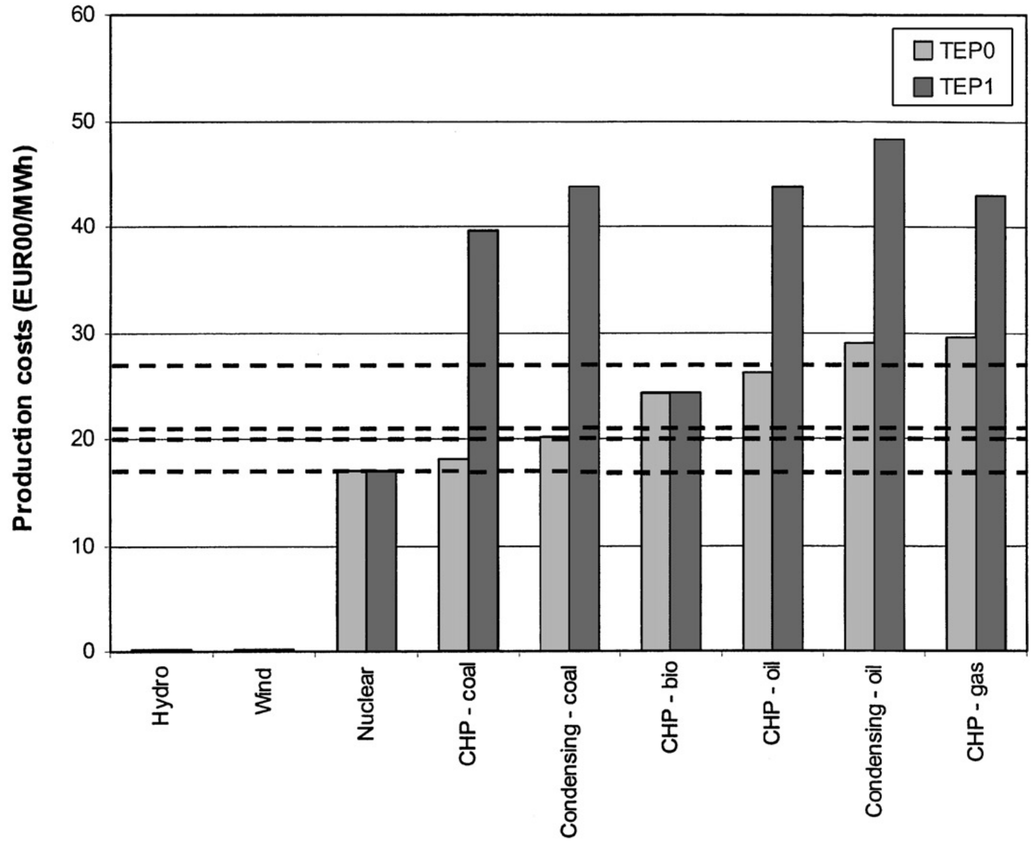

Fig. 6. Variable production costs without and with CO_2 emission limits (bars), and the spot prices (horizontal lines (TEP0-TGC0: 21 EUR00/MWh, TEP0-TGC1: 17 EUR00/MWh, TEP1-TGC0: 27 ERR00/MWh and TEP1-TGC1: 20 EUR00/MWh). Sweden 2010.

Table 3
2010 production at selected plants in some countries constructed between 2000 and 2010 in four cases (in TWh)

	Denmark	Finland	Germany	Norway	Sweden
TEP1-TGC0					
Wind	0.7	0	0	0	0
Hydro	0	0	0	15.5	0
Bio + waste	0.2	0	0.9	0	0
Total	0.9	0	0.9	15.5	0
TEP0-TGC1					
Wind	9.6	6.0	10.1	0	2.7
Hydro	0	0	0	0	0
Bio + waste	8.5	3.9	33.1	0	4.8
Total	18.1	9.9	43.2	0	7.6
TEP1-TGC1					
Wind	9.6	6.0	9.4	0	2.7
Hydro	0	0	0	0	0
Bio + waste	8.6	8.7	28.6	0	5.3
Total	18.2	14.8	38.0	0	8.1

the TEP1-TGC0 case is the dominant investment in hydropower in Norway. The TEP0-TGC1 and the TEP1-TGC1 in contrast motivate investments in wind power, biomass and waste-fuelled technologies in Denmark, Finland, Germany and Sweden. For countries outside both bubbles no extensive investments take place (not shown in the table).

The redistribution of income between different technologies and the resulting establishment of more capacity of the above mentioned technologies might have negative effect on the possibility of maintaining stable electricity conditions. Thus, enhancement of wind power in a situation with high renewable demand share combined with lower spot market prices will make it unattractive to invest in production capacity with fast regulation properties. Since capacity with fast regulation properties is necessary in an energy system with large amounts of wind power, the result may be reduced stability in the electricity system.

Table 4 shows, in relation to the TEP1-TGC1 case, where production of electricity from renewable energy sources will take place within the TGC bubble and compares this with the number of certificates (in TWh equivalents), that are to be bought in each of the countries. The table indicates that both Denmark and Finland produce an electricity surplus of around 10 TWh annually, while Germany and Sweden import similar amounts. With a TGC price of 50 EUR00/MWh, a yearly money flow of 500 million EUR00 from each of

Table 4
National renewable energy production and demand in 2010 in the TEP1-TGC1 case

	Denmark	Finland	Germany	Sweden
2010 Demand (TWh)	41.4	83.9	641.0	167.6
RE target (%)	29.0	31.3	12.5	60.0
RE target (TWh)	12.0	26.3	80.1	100.6
RE production (TWh)	22.2	36.5	69.1	91.1
RE production surplus (TWh)	10.2	10.2	−11.0	−9.5

Table 5
Import and export in Sweden and Poland (TWh)

	Poland		Sweden	
	Import	Export	Import	Export
TEP0-TGC0	1.6	3.3	10.0	2.5
TEP1-TGC0	0.0	8.6	20.6	12.8
TEP0-TGC1	6.4	2.7	6.4	11.4
TEP1-TGC1	1.6	2.7	4.9	8.5

the deficit countries will go to each of the surplus countries. In addition, the payment for electricity is according to the spot price.

Transmission between countries is motivated by spot price differences across borders with a transmission line. Table 2 shows the annual weighted average spot prices in the different countries in four of the cases (see identification in Table 1). The results primarily indicate that a stronger interconnection between Germany and Poland and Poland and the Baltic countries could be suggested. Also stronger connections between the Nordic countries and Central Europe (Germany and Poland) may be interesting, depending on the case.

From the relations between the environmental goals and the spot prices, it is seen that environmental goals affect transmission between countries within and outside a bubble. As an example consider Sweden (within) and Poland (outside), and assume for the sake of convenience that Poland does not have environmental goals. A transmission line links the two countries. Without environmental goals in Sweden and the other Nordic countries, the spot price will be lower in Poland, implying import of electricity to Sweden from Poland (possibly with transit to other countries). If the emission goal is strengthened in Sweden (and other countries in the bubble), the spot price in Sweden will increase further, and there is an economic motivation to increase the import even more if possible. This is indicated in Table 5. Growth in export to neighbouring countries from Poland can be seen, while Sweden representing a transmission entry to the emission bubble increases its import. The net balance between import and export, though, is the same since much of the import to Sweden is exported to other Nordic countries also at high prices. In other words, the strengthening of the emission goal in the Nordic counties implies (within the transmission possibilities) substitution of Nordic production by Polish production. The net impact on the environment in terms of emission depends on the electricity production system in the two countries. If, on the other hand, the renewable energy goal is strengthened in Sweden (and other countries in the renewable energy bubble), then the spot price in Sweden will decrease. This will imply an economic motivation to decrease the import to Sweden from Poland and, if the renewable energy goal is high, even to change to net export from Sweden to Poland. Thus, the strengthening of the renewable energy goal in the renewable energy bubble will imply substitution of Polish production by Swedish production. The net change in renewable energy production again depends on the electricity production system in the two countries. This can also be seen in Table 5.

5. Conclusions and perspectives

The paper has addressed a situation where goals for limitations on CO_2 emissions and/or introduction of renewable energy have been implemented through the establishment of international systems of exchange of TEPs and/or TGCs. Thus, one or two international markets are assumed to have been established in addition to the electricity market. The situation has been explicitly modelled at two levels of abstraction, one suitable for defining and analysing basic functionalities and one suitable for numerical analysis in relation to countries in the Baltic Sea Region.

The numerical simulations contribute an estimate of the prices of TEPs, TGCs and spot price electricity in the region depending on the assumptions regarding target setting for renewable energy and emission limitation. The results have been commented on in detail in Section 4; a general conclusion is that within the range of goals stipulated in the EU draft directive (23.6% renewable energy) and the Kyoto targets for emissions, prices are affected significantly: from –2 to +10 EUR00/MWh for electricity spot prices, TGC prices up to 50 EUR00/MWh, TEP prices up to 18 EUR00/t CO_2 and up to +15 EUR00/MWh on the consumer costs. This estimated increase will result in increased consumers' cost of electricity in the Nordic countries of up to 6 billion EURO annually.

It has been shown that such price changes have important consequences for the production and investment patterns in the electricity sector. The quantitative effects in these directions have been estimated, and as shown, the resulting patterns will be clearly different according to the specific numerical targets for the two goals. This in turn will determine the international exchange of electricity and the international trade in TEPs and TGCs. Thus, unlike before, when the location of production capacity was determined to a large extent by national energy self-sufficiency, the motivation for establishing new production technology is now also determined by international arrangements in relation to renewable energy and emission limitations. As shown, an immediate consequence is increased pressure on transmission lines. The transmission quantities indicated in the analysis will clearly motivate or force investments in increased international transmission capacity. If this does not take place and result in a segmentation of the electricity spot market, some of the efficiency gains, which are the motivation for the introduction of TEP and TGC markets, will be lost.

There are other perspectives of the restructuring of the electricity system that may result from the introduction of TEP and TGC markets. Thus, a significant increase in wind power will have to be counterbalanced by measures such as access to production technologies with fast regulating properties and/or that may maintain voltage stability. However, one consequence of the pursuit of a renewable energy goal is to reduce the spot price of electricity—therefore the motivation for investments in traditional technologies with such desirable qualities will be lower. In other words, the price signals of TGCs (and to some extent also TEPs) that will enhance wind power investments will simultaneously hamper investments in technologies that are a precondition for extensive use of wind power technologies.

Acknowledgements

The authors are grateful to Poul Erik Morthorst for inspiring discussions during the early stages of the work and to two anonymous referees for constructive comments at later stages.

Appendix A

The purpose of this appendix is to define a mathematical model of the problem of introduction of TEPs and TGCs markets in addition to the electricity market in an international context. Further a compact derivation is given of the prices in the markets, their relationship with the quotas and the international trade. Also expressions for producers' and consumers' surplus are derived along with relaxation and monotonicity properties.

Consider the following model:

$$\max \left[\sum_{c \in C} D^c(d^c) - \sum_{i \in I} f_i(g_i) \right], \tag{A.1}$$

$$\sum_{i \in I} g_i^c + \sum_{a \in C} (x^{(a,c)} - x^{(c,a)}) = d^c + o_1^c, c \in C, \tag{A.2}$$

$$\sum_{c \in C_R} \sum_{i \in I_R} g_i^c \sum_{c \in C_R} \alpha^c d^c + o_2, \tag{A.3}$$

$$\sum_{c \in C_M} \sum_{i \in I_M} \phi_i(g_i^c) \sum_{c \in C_M} \bar{m}^c, \tag{A.4}$$

$$0 x^{(a,b)} \bar{x}^{(a,b)}, a \in C, b \in C, \tag{A.5}$$

$$_i(g_i) 0, i \in I. \tag{A.6}$$

Here the individual production units are identified by the index i, and the index set I holds all units. Each unit in I is classified as either renewable or emitting, indicated by belonging to one of the index sets I_R and I_M, respectively, where I_R and I_M are mutually exclusive subsets of I, and together constitute I. The set C is the set of countries c. Two subset are defined on C viz., C_R holding the countries in the renewable bubble, C_M holding the countries in the emission bubble. C_R and C_M need not be mutually exclusive, nor together constitute C. The electricity production of unit i is denoted g_i; the notation g_i^c indicates that unit i is located in country c. A notation like $\sum_{i \in I} g_i^c$ is used to indicate the summation over those i that are located in c.

The function D^c describes for country c the consumers' benefit as a function of electricity consumption d^c. The cost of the production g_i on unit i is given by $f_i(g_i)$ and the associated emission by $\phi_i(g_i)$; $\phi_i(g_i)0$ for all units, and by definition $\phi_i(g_i) = 0$ for $i \in I_R$. Electricity export from country a to country b is indicated by $x^{(a,b)}$. Electricity consumption in country c is d^c.

The variables in model (A.1)–(A.6) are production g_i^c, transmission $x^{(a,b)}$ and consumption d^c. The objective function in (A.1) describes the sum of producers' and consumers' surplus which is to be maximised. Eq. (A.2) describes the balance between supply and demand of electricity in country c. The parameters o_1^c and o_2 will be discussed below; they take the value zero. As seen, international transmission is permitted within the limits given in Eq. (A.5); transmission from a country to itself is not possible, i.e., $\bar{x}^{(c,c)} = 0$. Eq. (A.3) describes the requirement that a certain part of total consumption in the countries in C_R (derived from the quantities $\alpha^c d^c$ in the individual countries) must be covered by renewable electricity. Eq. (A.4) describes the limitation of total emission in the countries in C_M where $\bar{m}^c$ is the quantity in country c. Eq. (A.6) represents all other constraints on the individual production units.

Associate the Lagrange multipliers λ^c, ρ and μ to (A.2), (A.3) and (A.4), respectively, and define the

Lagrangian as

$$L = \sum_{c\in C} D^c(d^c) - \sum_{i\in I} f_i(g_i) + \left(\sum_{c\in C}\lambda^c\left(\sum_{i\in I} g_i^c + \sum_{a\in C}(x^{(a,c)} - x^{(c,a)}) - d^c - o_1^c\right)\right) + \left(\rho\left(\sum_{c\in C}\left(\sum_{i\in I_R} g_i^c - \alpha^c d^c\right)\right) - o_2\right) - \left(\mu\sum_{c\in C_M}\left(\sum_{i\in I_M}\phi_i(g_i^c) - \bar{m}^c\right)\right). \tag{A.7}$$

For simplicity, Eqs. (A.5) and (A.6) have been not been included in the definition of the Lagrangian; Eq. (A.5) will be discussed later.

Now assume that all the functions are once continuously differentiable, that a regularity condition holds and that the solution and the Lagrange multipliers are unique. Then the following interpretations may be given in relation to the optimal solution and Lagrange multipliers.

The value $L/o_1^c = \lambda^c$ is the marginal cost of electricity production in country c, i.e. the additional cost of producing one more unit of electricity. This value may further be taken as the spot price of electricity in that country. Observe that this marginal cost disregards the additional cost associated with the requirement given in (A.3) and that it can therefore not be interpreted as the marginal cost of satisfying increased consumption, see below.

The value $L/o_2 = \rho$ may be interpreted as the marginal cost of increasing the production of renewable electricity. This value may further be taken as the price of the TGC. Observe that this value is not the total marginal cost of the renewable energy production, but only that part which is in addition to the marginal cost given by λ^c for the country c considered.

The marginal cost associated with increasing production of renewable electricity by a small amount and at the same time increasing consumption in country c by the same amount is given as $L/o_1^c + L/o_2 = \lambda^c + \rho$.

The marginal cost of satisfying increased consumption in country c is given as $L/d^c = \lambda^c + \alpha^c\rho$. This may be taken as the consumers' combined electricity and TGC price, i.e. the consumers' marginal cost of acquiring electricity.

The marginal cost of increasing α^c is given as $\partial L/\partial\alpha^c = \rho d^c$.

The marginal cost of increasing emission is given as $L/\bar{m}^c = -\mu$. The marginal cost of reducing emission is then μ. This value may further be taken as the price of the TEP. Observe that this values is the same for all countries in C_M, in contrast to the results relative to renewable energy.

Now consider countries a and b that have a transmission line between them. Let λ^a and λ^b be the associated multipliers relative to (A.2). If transmission between the two countries is not actively constrained by (A.5), the optimality condition specifies that the values $L/x^{(a,b)} = \lambda^a - \lambda^b$ and $L/x^{(b,a)} = \lambda^a - \lambda^b$ are zero, i.e. the spot prices are identical in the two countries. If on the other hand $\lambda^a < \lambda^b$, then country a has maximum export $\bar{x}^{(a,b)}$ to country b and if $\lambda^a > \lambda^b$ the transmission is $\bar{x}^{(b,a)}$, i.e. maximum in the other direction.

The international trade of electricity is given by the optimal values of $x^{(a,b)}$. Assuming that all emission requires a corresponding TEP, the need for TEP in country c is given as $\sum_{i\in I_M}\phi_i(g_i^c)$. It is assumed that the quantity of TEP issued in country c corresponds to $\bar{m}^c$. The net import of TEP to country c is therefore $(\sum_{i\in I_M}\phi_i(g_i^c) - \bar{m}^c)$. The need for TGC in country c is given as $\alpha^c d^c$; the net import of TGC to country c is therefore $(\sum_{i\in I_R i} g_i^c - \alpha^c d^c)$.

For countries $c\in C_R$ the consumers' total cost of acquiring electricity is $(d^c(\lambda^c + \alpha^c\rho))$, and their surplus is $(D^c(d^c) - d^c(\lambda^c + \alpha^c\rho))$. For countries not in C_R the same expressions apply with $\alpha^c = 0$. Total consumers' surplus is found by summation over all indexes c.

Producer's surplus with production quantity g_i^c on unit i is $(\lambda^c g_i^c - f_i(g_i^c) + \rho g_i^c - \mu\phi_i(g_i^c))$. The penultimate term represents the income from sale of TGC (zero if $i\in I_M$). The last term represents the cost of acquiring TEP corresponding to the emission (zero if $i\in I_R$). If grand fathering is assumed such that the owner of unit $i\in I_M$ has a permit of $\bar{m}_i^c$ then this producer's surplus is $(\lambda^c g_i^c - f_i(g_i^c) + (\bar{m}_i^c - \phi_i(g_i^c))\mu)$. Total producers' surplus is found by summation over all indexes (c, i).

The following are basic properties of model (A.1)–(A.6).

Eq. (A.4) may be seen as a combination (relaxation) of a number of equations $\sum_{i\in I_M}\phi_i(g_i^c)\bar{m}^c$, one for each country in C_M. Hence, model (A.1)–(A.6) may be seen as one of cooperation between the countries in C_M in contrast to the model where each country has individual limits $\bar{m}^c$. From properties of relaxation it follows that the total production cost (i.e., the optimal value of Eq. (A.1)) is not larger with cooperation as in (A.1)–(A.6) than with individual limits. Similar considerations apply to Eq. (A.3).

Now assume in addition to the above that all functions involved are convex, except D^c which is assumed concave. Then the following holds true: the value of λ^c increases weakly with increasing d^c; the value of ρ increases weakly with increasing α^c; the value of μ increases weakly with decreasing $\bar{m}^c$.

In relation to investments in new electricity production technology, the following clarification may be made. Let the capacity already existing at the beginning of the period be given by $\bar{g}_i$ for unit i, then this is included in (A.6) as $g_i\bar{g}_i$. New capacity may be constructed at specified costs. Therefore one possible specification of the combined costs of production and investment is the following. Assume that production on a new unit i takes place at a constant marginal cost of β_i, and that new capacity may be constructed at a cost of γ_i. Then the cost function f_i for this unit is given as $(\beta_i g_i + \gamma_i g_i)$. With such or any other convex continuously differentiable form of f_i the above conclusions hold true.

Based on these observations the extension to a multi-year dynamic model, where new capacity may be invested at the beginning of each year, is straightforward.

Finally, also observe that the extension to a situation where each year is subdivided into time segments to reflect diurnal and seasonal variations is straightforward, although tedious.

Also with such extensions the above conclusions hold true.

A description of the more detailed representation of the dynamic production, transmission and demand systems used in the numerical model calculations may be found in 'The Balmorel Model: Theoretical Background', see www.Balmorel.com.

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Erratum

Erratum to "Co-existence of electricity, TEP, and TGC markets in the Baltic Sea Region" [Energy Policy 31 (2003) 85–96]☆

Magnus Hindsberger, Malene Hein Nybroe, Hans F. Ravn*, Rune Schmidt

Elkraft System, Lautruphøj, DK-2750, Denmark

The publishers regret that there were errors in Appendix A(pp. 94–96). The correct Appendix is given below.

Appendix A

The purpose of this appendix is to define a mathematical model of the problem of introduction of TEPs and TGCs markets in addition to the electricity market in an international context. Further a compact derivation is given of the prices in the markets, their relationship with the quotas and the international trade. Also expressions for procedures' and consumers' surplus are derived along with relaxation and monotonicity properties.

Consider the following model:

$$\max\left[\sum_{I\in C} D^c(d^c) - \sum_{i\in I} f_i(g_i)\right], \tag{A.1}$$

$$\sum_{i\in I} g_i^c - \sum_{a\in C}\left(x^{(a,c)} - x^{(c,a))}\right) = d^c + o_1^c, c\in C, \tag{A.2}$$

$$\sum_{c\in C_R}\sum_{i\in I_R} g_i^c \geqslant \sum_{c\in C_R} \alpha^c d^c + o_2, \tag{A.3}$$

$$\sum_{c\in C_M}\sum_{i\in I_M} \phi_i(g_i^c) \leqslant \sum_{c\in C_M} \bar{m}^c, \tag{A.4}$$

$$0\leqslant x^{(a,b)} \leqslant \bar{x}^{(a,b)},\ a\in C,\ b\in C, \tag{A.5}$$

$$\Phi_i(g_i)\leqslant 0, i\in I. \tag{A.6}$$

Here the individual production units are identified by the index i, and the index set I holds all units. Each unit in I is classified as either renewable or emitting, indicated by belonging to one of the index sets I_R and I_M, respectively, where I_R and I_M are mutually exclusive subsets of I, and together constitute I. The set C is the set of countries c. Two subsets are defined on C viz., C_R holding the countries in the renewable bubble, C_M holding the countries in the emission bubble. C_R and C_M need not be mutually exclusive, nor together constitute C. The electricity production of unit i is denoted g_i; the notation g_i^c indicates that unit i is located in country c. A notation like $\sum_{i\in I} g_i^c$ is used to indicate the summation over those i that are located in c.

The function D^c describes for country c the consumers' benefit as a function of electricity consumption d^c. The cost of the production g_i on unit i is given by $f_i(g_i)$ and the associated emission by $\phi_i(g_i)$; $\phi_i(g_i)\geqslant 0$ for all units, and by definition $\phi_i(g_i) = 0$ for $i\in I_R$.Electricity export from country a to country b is indicated by $x^{(a,b)}$. Electricity consumption in country c is d^c.

The variables in model (A.1)–(A.6) are production g_i^c, transmission $x^{(a,b)}$ and consumption d^c. The objective function (A.1) describes the sum of producers' and consumers' surplus which is to be maximised. Eq. (A.2) describes the balance between supply and demand of electricity in country c. The parameters o_1^c and o_2 will be discussed below; they take the value zero. As seen, international transmission is permitted within the limits given in Eq. (A.5); transmission from a country to itself is not possible, i.e., $\bar{x}^{(c,c)} = 0$. Eq. (A.3) describes the requirement that a certain part of total consumption in the countries C_R (derived from the quantities $\alpha^c d^c$ in the individual countries) must be covered by renewable electricity. Eq. (A.4) describes the limitation of total emission in the countries in C_M where $\bar{m}^c$ is the quantity in country c. Eq. (A.6) represents all other constraints on the individual production units.

Associate the Lagrange multipliers λ^c, ρ and μ to (A.2), (A.3) and (A.4), respectively, and define the Lagrangian as

$$L = \sum_{c\in C} D^c(d^c) - \sum_{i\in I} f_i(g_i)$$
$$+ \left(\sum_{c\in C}\lambda^c\left(\sum_{a\in I} g_i^c + \sum_{a\in C}(x^{(a,c)} - x^{(c,a)}) - d^c - o_1^c\right)\right)$$

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*Corresponding author. Tel.: +45-4487-3618; fax: +45-4487-3210.
E-mail address: hry@elkraft.dk (H.F. Ravn).

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$$+\left(\rho\left(\sum_{c\in C}\left(\sum_{i\in I_R} g_i^c-\alpha^c d^c\right)\right)-o_2\right)$$
$$-\left(\mu\sum_{c\in C_M}\left(\sum_{i\in I_M}\phi_i(g_i^c)-\bar{m}^c\right)\right). \tag{A.7}$$

For simplicity, Eqs. (A.5) and (A.6) have not been included in the definition of the Lagrangian; Eq. (A.5) will be discussed later.

Now assume that all the functions are once continuously differentiable, that a regularity condition holds and that the solution and the Lagrange multipliers are unique. Then the following interpretations may be given in relation to the optimal solution and Lagrange multipliers.

The value $\partial L/\partial o_1^c=\lambda^c$ is the marginal cost of electricity production in country c, i.e. the additional cost of producing one more unit of electricity. This value may further be taken as the spot price of electricity in that country. Observe that this marginal cost disregards the additional cost associated with the requirement given in (A.3) and that it can therefore not be interpreted as the marginal cost of satisfying increased consumption, see below.

The value $\partial L/\partial o_2=\rho$ may be interpreted as the marginal cost of increasing the production of renewable electricity. This value may further be taken as the price of the TGC. Observe that this value is not the total marginal cost of the renewable energy production, but only that part which is in addition to the marginal cost given by λ^c for the country c considered.

The marginal cost associated with increasing production of renewable electricity by a small amount and at the same time increasing consumption in country c by the same amount is given as $\partial L/\partial o_1^c+\partial L/\partial o_2=\lambda^c+\rho$.

The marginal cost of satisfying increased consumption in country c is given as $\partial L/\partial d^c=\lambda^c+\alpha^c\rho$. This may be taken as the consumers' marginal cost of acquiring electricity.

The marginal cost of increasing α^c is given as $\partial L/\partial\alpha^c=\rho d^c$.

The marginal cost of increasing emission is given as $\partial L/\partial\bar{m}^c=-\mu$. The marginal cost of reducing emission is then μ. This value may further be taken as the price of the TEP. Observe that this values is the same for all countries in C_M, in contrast to the results relative to renewable energy.

Now consider countries a and b that have a transmission line between them. Let λ^a and λ^b be the associated multipliers relative to (A.2). If transmission between the two countries is not actively constrained by (A.5), the optimality condition specifies that the values $\partial L/\partial x^{(a,b)}=\lambda^a-\lambda^b$ and $\partial L/\partial x^{(b,a)}=\lambda^a-\lambda^b$ are zero, i.e. the spot prices are identical in the two countries. If on the other hand $\lambda^a<\lambda^b$, then country a has maximum export $\bar{x}^{(a,b)}$ to country b and if $\lambda^a>\lambda^b$ the transmission is $\bar{x}^{(b,a)}$, i.e. maximum in the other direction.

The international trade of electricity is given by the optimal values of $x^{(a,b)}$. Assuming that all emission requires a corresponding TEP, the need for TEP in country c is given as $\sum_{i\in I_M}\phi_i(g_i^c)$. It is assumed that the quantity of TEP issued in country c corresponds to $\bar{m}^c$. The net import of TEP to country c is therefore $(\sum_{i\in I_M}\phi_i(g_i^c)-\bar{m}^c)$. The need for TGC in country c is given as $\alpha^c d^c$; the net import of TGC to country is therefore $(\sum_{i\in I_R} g_i^c-\alpha^c d^c)$.

For countries $c\in C_R$ the consumers' total cost of acquiring electricity is $(d^c(\lambda^c+\alpha^c\rho))$, and their surplus is $(D^c(d^c)-d^c(\lambda^c+\alpha^c\rho))$. For countries not in C_R the same expressions apply with $\alpha^c=0$. Total consumers' surplus is found by summation over all indexes c.

Producer's surplus with production quantity g_i^c on unit i is $(\lambda^c g_i^c-f_i(g_i^c)+\rho g_i^c-\mu\phi_i(g_i^c))$. The penultimate term represents the income from sale of TGC (zero if $i\in I_M$). The last term represents the cost of acquiring TEP corresponding to the emission (zero if $i\in I_R$). If grand fathering is assumed such that the owner of unit $i\in I_M$ has a permit of $\bar{m}_i^c$ then this producer's surplus is $(\lambda^c g_i^c-f_i(g_i^c)+(\bar{m}_i^c-\phi_i(g_i^c))\mu)$. Total producers' surplus is found by summation over all indexes (c,i).

The following are basic properties of model (A.1)–(A.6).

Eq. (A.4) may be seen as a combination (relaxation) of a number of equations $\sum_{i\in I_M}\phi_i(g_i^c)\leqslant\bar{m}^c$, one for each country in C_M. Hence, model (A.1)–(A.6) may be seen as one of cooperation between the countries in C_M in contrast to the model where each country has individual limits $\bar{m}^c$. From properties of relaxation it follows that the total production cost (i.e., the optimal value of Eq. (A.1)) is not larger with cooperation as in (A.1)–(A.6) than with individual limits. Similar considerations apply to Eq. (A.3).

Now assume in addition to the above that all functions involved are convex, except D^c which is assumed concave. Then the following holds true: the value of λ^c increases weakly with increasing d^c; the value of ρ increases weakly with increasing α^c; the value of μ increases weakly with decreasing $\bar{m}^c$.

In relation to investments in new electricity production technology, the following clarification may be made. Let the capacity already existing at the beginning of the period be given by $\bar{g}_i$ from unit i, then this is included in (A.6) as $g_i\leqslant\bar{g}_i$. New capacity may be constructed at specified costs. Therefore one possible specification of the combined costs of production and investment is the following. Assume that production on a new unit i takes place at a constant marginal cost of β_i, and that new capacity may be constructed at a cost of γ_i. Then the cost function f_i for this unit is given as $(\beta_i g_i+\gamma_i g_i)$. With such or any other convex continuously differentiable form of f_i the above conclusions hold true.

Based on these observations the extension to multi-year dynamic model, where new capacity may be invested at the beginning of each year, is straightforward.

Finally, also observe that the extension to a situation where each year is subdivided into time segments to reflect diurnal and seasonal variations is straightforward, although tedious.

Also with such extensions the above conclusions hold true.

A description of the more detailed representation of the dynamic production, transmission and demand systems used in the numerical model calculations may be found in 'The Balmorel Model: Theoretical Background', see www.Balmorel.com.