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Integration of Tradable Green Certificate Markets: What can be expected?

by

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Abstract:

Recently, many countries have introduced systems of tradable green certificates (TGCs) in order to increase the proportion of their electricity supply obtained from renewable sources. The main objective of this paper is to investigate the analytics of a TGC system of the Nordic type when integrated within several countries and to determine what can be expected from the system when applied in a real world setting. Both an analytical and a partial equilibrium version of the model are applied. In particular, we ask whether it is possible to derive analytically clear cut results with respect to how the system affects generation of electricity from renewable resources, and from carbon emitting resources, in the same way as it is possible for other known policy instruments such as an emission permit system or a plain carbon emission tax. A key result is that TGCs may be an imprecise instrument for regulating the generation of green electricity and that the combination of TGCs with a system of tradable emission permits may yield outcomes contrary to the intended purpose.

JEL classifications: C7; Q28; Q42; Q48

Key words: Renewable energy, electricity, green certificates, emissions trading

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1. Introduction[3]

Many countries pursue policies to increase the share of renewable energy in their total energy consumption. For example, the EU has an explicit target to increase its share of "green" electricity, generated from renewable energy sources, from its current level of 14% to 22% by 2010 (EU/COM, 2000). Similar targets exist for the USA (e.g., see EPA, 2003). Until recently, the generation of green electricity had been stimulated by various subsidy schemes, including subsidized investments, tax relief, and direct subsidies per unit of green electricity generated. However, with the liberalization of electricity markets, interest has shifted towards other subsidy measures. One proposition that has become popular is to introduce systems of tradable green certificates (TGCs). Such systems tend to have different designs in different countries, but a common feature is that they seek to replace direct public subsidies for renewable energy with incentive systems that use the market mechanism. More precisely, the objective is to create a market where various kinds of green electricity compete on equal terms to relieve the government of the burden of direct involvement in the electricity sector's investment decisions.

Since 1998, the Netherlands has applied a system of "green labeling", which is a voluntary system of green certificates. The UK and Sweden have compulsory systems that use the market mechanism more directly for TGC trading. These systems differ significantly from the more established feed-in tariff subsidy schemes that exist in countries such as Germany (see Butler and Neuhoff, 2004). Many European countries participate in the *Renewable Energy Certificate System (RECS)* that, although not a support scheme itself, facilitates many support schemes for green energy.[4] In addition, several countries outside the EU have shown an interest in introducing TGC systems, including Australia, USA, China, and India (see Giovinetto, 2003).

In 2002, the UK introduced a TCG system called the *UK Renewables Obligation Certificate (ROC) Market*. Sweden introduced its system in 2003. The Norwegian Parliament has not yet decided but plans exist that Norway and Sweden will start

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[4] RECS is not restricted by national boundaries. It provides a mechanism for representing production of a MWh of renewable energy by a unique certificate, which can be transferred from owner to owner before being used as proof of generation, or exchanged for financial support (http://www.trecin.com).

trading TGCs at some future date, thus creating the first integrated TGC market involving several countries.[5] As well as analyzing the general functioning of a TGC market of the Nordic type,[6] this paper discusses how a TGC market is expected to perform when it expands to include several countries.

As in any other market, the markets for TGCs consist of suppliers and buyers. Suppliers are the producers of green electricity who receive an amount of TGCs corresponding to the amount of green electricity they generate. The suppliers may sell these TGCs on the TGC market. In this way, the producers receive both the wholesale price and the TGC price per MWh of green electricity generated. Buyers of TGCs are the retailers or consumers, who are obliged by the government to keep a certain amount of TGCs in relation to the total amount of electricity they consume (i.e., both green and "black" electricity). This requirement is referred to as the "percentage requirement". Thus, the demand for TGCs is derived simply as a percentage of the total end use demand for electricity. Based on supply and demand, a single TGC price may then be established. The percentage requirement is the primary policy instrument[7] that the government may use in order to attain the targets for green electricity generation and for the mix of black and green electricity. Both Sweden and the UK have specific plans for escalating their percentage requirements.

Along with the development of the TGC markets in Europe, a more general and comprehensive system of emission permits trading (ETS)[8] is about to emerge in the EU. The simple idea underlying the ETS is that the emission permit price will add to

[5] In 2004, Nord Pool began trading TGCs on the Swedish market. TGC prices are posted on the Nord Pool web page at www.nordpool.no.

[6] One particular characteristic of the Nordic system is that only small new hydro power plants qualify for TGCs, whereas existing large hydro power plants do not. Hence, even though electricity generation in a country like Norway is based on almost 100% waterpower, only electricity generated by biomass, wind, and new small hydro power plants' biomass will count as green electricity in the TGC system. For this reason, it is likely that the percentage requirement will be set at a rather low level (i.e., 2–5%).

[7] As the UK system the Nordic TGC system sanctions retailers/ consumers for not complying with the system. Hence, in the Swedish system the retailers have to pay a penalty for not having sufficient TGCs. The penalty is set equal to 150% of the annual average price for the period in question. One basic difference between the UK system and the Nordic system is that the former allows recycling of revenues from the buy-out payments required of electricity companies that do not obtain sufficient ROCs. These buy-out payments are recycled to suppliers that have presented ROCs. By contrast, the Norwegian system does not involve any recycling of the corresponding penalty payments.

[8] The EU Emissions Trading Scheme (ETS) is based on the EU Directive of Emissions Trading, which was adopted in July 2003 (European Commission, 2003) and was put into effect in 2005. At first, it will comprise only carbon emissions, but other greenhouse gases will be included later. The system covers emissions from several sectors, including electricity and district heating.

the cost of using a carbon emitting resource, the cost increment being in proportion to the emissions per unit of the resource used. As a result, input substitution in the long run is expected to take place in electricity generation, away from coal and gas power towards hydro, wind, and nuclear power.[9] Hence, even though this system is not directly targeted at increasing the share of *renewables* in electricity provision, clearly the system will have an influence on the relative cost of providing green electricity. In order to take account of this influence we investigate how the TGC market and the electricity market are affected by a carbon emission permit price or alternatively a carbon tax. [10]

The main objective of this paper is to investigate the analytics of a TGC system of the Nordic type when integrated within several countries and try to determine what can be expected from the system when applied in a real world setting. In particular, we ask whether it is possible to derive analytically clear cut results with respect to how the system affects generation of electricity from renewable resources, and from carbon emitting resources, in the same way as it is possible for other known policy instruments such as an emission permit system or a plain carbon emission tax.

To some extent similar problems have been investigated earlier. Amundsen and Mortensen (2001) investigated aspects of the percentage requirement for domestic TGC and electricity markets. TGC price volatility and banking were dealt with by Amundsen et al. (2006). Also, numerical models of TGC and electricity markets have been formulated and analyzed (e.g., Bergman and Radetzki, 2003; Bye 2003; Nese, 2003). Furthermore, the relationship between TGCs and carbon emission permits have been addressed earlier; e.g., in Finon and Menanteau (2003), Jensen and Skytte (2003), and Unger and Ahlgren (2003). However, unlike these papers, our focus is on the integration of domestic TGC markets into a joint TGC market and on the analytics of the effects of the major policy measure, the percentage requirement, and of a carbon emission permit price/ carbon tax.

[9] Short run input substitution will be limited by available technological possibilities. Therefore, the immediate short run effect will probably be substitution from e.g. coal towards natural gas.

[10] Both the Nordic TGC market and the Nordic electricity market are too small to significantly impact the ETS system that covers all of Europe. Hence, we limit our analysis to consider the effects of an exogenous shift of the emission permit price/emission tax.

In the following we formulate both an analytic model to derive general results and a numerical model to assess the functioning of the combined TGC and electricity markets for Norway and Sweden in particular. The paper proceeds as follows. First, we consider the joint functioning of a TGC market and an electricity market under autarky, focusing on questions such as how the generation of green electricity is affected by the percentage requirement, or by an emission permit price or an emission tax. Then, we analyze the case where two countries trade in electricity, but not in TGCs. This situation may be considered an interim case before a complete set of markets is in place. We then proceed to analyze cases involving both a common TGC market and a common electricity market. Thereafter, results from the numerical model are presented. Finally, we discuss the analytical and numerical results obtained and conclude the paper.

2. The model under autarky

In order to analyze the interplay between the electricity market and the TGC market under autarky, we apply the following symbols and functional relationships.

$p =$ End-user price of electricity

$s =$ Price of TGCs

$q =$ Wholesale price of electricity

$x =$ Total consumption of electricity

$y =$ Production of "black" electricity

$z =$ Production of "green" electricity

$\alpha =$ Green electricity required as a proportion of total electricity consumption ("percentage requirement")

$\tau =$ Parameter representing a carbon emission permit price or a carbon tax

$g^d =$ Demand for TGCs

$g^s =$ Supply of TGCs

$p(x)$: Inverse demand function of electricity, where $(\partial p(x)/\partial x) = p' < 0$

$c = c(y;\tau)$: Industry cost function[11] for black electricity with emission constraints. We assume $\frac{\partial c}{\partial y} > 0$, $\frac{\partial^2 c}{\partial y^2} \geq 0$, and $\frac{\partial^2 c}{\partial y \partial \tau} > 0$.[12]

$h = h(z)$: Industry cost function for green electricity, where $\frac{\partial h}{\partial z} > 0$ and $\frac{\partial^2 h}{\partial z^2} > 0$

$\Pi = \Pi(.)$: Profit function

2.1. First-order conditions and the equilibrium

In this model, the electricity producers supply a common wholesale market within which a single wholesale electricity price is established. Retailers purchase electricity on the wholesale market and TGCs on the TGC market. The electricity is distributed to end users and a single end-user price is established. It is assumed that perfect competition prevails in all markets, with many producers of both black and green electricity, many retailers, and many end users. Hence, all agents treat the various prices as given by the market.

The producers maximize:

$$\Pi(y) = qy \ + [q+s]z - c(y;\tau) - h(z) .$$

The first-order conditions for black, respectively, green electricity generation are:

$$q = \frac{\partial c(y,\tau)}{\partial y} \quad , \quad q + s = \frac{\partial h(z)}{\partial z} .$$

For each unit of electricity (i.e. MWh) purchased in the wholesale market and sold on to end users, retailers have to pay the wholesale price plus a share α of the TGC price.

[11] The industry cost function is derived by "horizontal addition" of the individual cost functions; i.e., the cost of aggregate market supply is minimized. Using the industry cost function avoids using messy notation to describe individual decisions and our prime interest is in the equilibrium market solution, not individual decisions. However, little detail is lost by this approach as individual first-order conditions for electricity producers correspond directly to those derived in the analysis; e.g., conditions 3) and 4) in the main text.

[12] The cost function for black electricity conditional on an emission permit price or an emission tax may be derived from a standard cost minimization problem, with the additional constraint that a permit price or a tax will have to be paid per unit carbon emitted.

For simplicity, electricity distribution is assumed costless.[13] With a large number of retailers, the competitive equilibrium established by the market must be characterized by: $p = q + \alpha s$. Otherwise, we assume that the amount of TGCs is measured in the same unit as the amount of green electricity. Thus, the demand for TGCs is given by $g^d = \alpha x$ and the supply by $g^s = z$.

Denoting equilibrium prices and quantities by starred symbols, the equilibrium of the two markets is characterized by:

1) $p(x^*) = q^* + \alpha s^*$;

2) $x^* = y^* + z^* = \dfrac{z^*}{\alpha}$;

3) $q^* = \dfrac{\partial c(y^*, \tau)}{\partial y}$;

4) $q^* + s^* = \dfrac{\partial h(z^*)}{\partial z}$.

Inserting 2), 3), and 4) into 1), we find that the end-user price in equilibrium may be written as a linear combination of the marginal costs of black and green electricity:

5) $p(x^*) = (1-\alpha)\dfrac{\partial c(y^*, \tau)}{\partial y} + \alpha \dfrac{\partial h(z^*)}{\partial z}$.

From 2), we see that $z^* = \alpha x^*$ and $y^* = (1-\alpha)x^*$.

2.2. The effects of the percentage requirement

In the TGC systems, the percentage requirement is perceived as a policy instrument to determine the amount of green electricity in end-use consumption. However, because the requirement is set as a percentage and not as a specific quantity, it is not necessarily true that an increase of the percentage requirement leads to an increase of green electricity generation. The share of green electricity generation in total electricity

[13] This assumption does not affect our qualitative results. In the numerical model to follow we do, however, include distribution costs.

consumption may well increase even if green electricity generation declines, if there is a sufficient reduction of electricity consumption and of black electricity generation.[14] In the following section, we study these effects in more detail.

To examine the effect of an increase in the percentage requirement[15] (i.e., $\frac{dz^*}{d\alpha}$) on the generation of green electricity, we substitute $x^* = \frac{z^*}{\alpha}$ and $y^* = \frac{(1-\alpha)z^*}{\alpha}$ into (5) and take the implicit derivates. Hence, omitting the starred symbols for the sake of simplicity, we obtain:

$$\frac{dz}{d\alpha} = \frac{\alpha s + x\left[\frac{\partial p}{\partial x} - (1-\alpha)\frac{\partial^2 c}{\partial y^2}\right]}{D}, \text{where } D = \left[\frac{\partial p}{\partial x} - (1-\alpha)^2\frac{\partial^2 c}{\partial y^2} - \alpha^2\frac{\partial^2 h}{\partial z^2}\right].$$

An inspection of the signs shows that the denominator is negative, whereas the numerator is indeterminate. Hence, the effect on green electricity generation is indeterminate.

With respect to the effect on black electricity generation we obtain:

$$\frac{dy}{d\alpha} = \frac{(1-\alpha)s + x\left[\alpha\frac{\partial^2 h}{\partial z^2} - \frac{\partial p}{\partial x}\right]}{D} < 0.$$

Inspection of signs shows that the numerator is positive, whereas the denominator is negative. The generation of black electricity is reduced as the percentage requirement increases.

With respect to the total electricity consumption, we find:

[14] In the Swedish system, however, there is no doubt that the intention of the TGC market is to stimulate an increase of capacity for generating green electricity. For this reason, our focus throughout the paper will be on how the absolute generation of green electricity is affected.

[15] The results in this paragraph represent a generalization of results in Amundsen and Mortensen (2001).

$$\frac{dx}{d\alpha} = \frac{s + x\left[\alpha \frac{\partial^2 h}{\partial z^2} - (1-\alpha)\frac{\partial^2 c}{\partial y^2}\right]}{D}.$$

Inspection of signs shows that this expression is generally indeterminate. However, if the marginal cost of black electricity is constant (i.e., $\frac{\partial^2 c}{\partial y^2} = 0$), we easily see that $\frac{dx}{d\alpha} < 0$. Thus, an increase of the percentage requirement will lead to a reduction of total electricity consumption. However, the impact on green electricity generation remains indeterminate. In addition, the effects depend on the level of the percentage requirement, α.[16] For example, if $\alpha = 0$, then $\frac{dz}{d\alpha} > 0$, whereas $\frac{dx}{d\alpha}$ is indeterminate.

Hence, in conclusion, the introduction of a TGC system of the Nordic type does not necessarily lead to greater green electricity generation, but it *does* lead to a reduction of black electricity generation. Furthermore, the effect on total electricity generation is indeterminate.

2.3. The effects of the emission permit price/emission tax

In order to investigate the equilibrium effects of increased emission permit price/emission tax on green electricity, we take the implicit derivate of 5) with respect to τ and obtain:

$$\frac{dz}{d\tau} = \frac{\alpha(1-\alpha)\frac{\partial^2 c}{\partial y \partial \tau}}{D} < 0 \qquad .$$

With the assumed cross effects of the marginal cost function of black electricity it follows that the numerator is positive so that the total effect is negative. Hence, increased emission permit price/emission tax will *not* lead to an increase in the generation of green electricity. On the contrary, generation of green electricity will

[16] By simplifying the functional forms of the model, for example by assuming linear or constant elastic demand and linear marginal cost functions, it is possible to study in more detail how the electricity consumption changes as the percentage requirement increases from 0 to 100%; see Bye (2003).

decline.[17] As $z^* = \alpha x^* = \alpha(1-\alpha)y^*$, both the generation of black electricity and the total consumption will also decline.

It may seem paradoxical that an increased emission price can actually lead to a reduction in the generation of green electricity, as this normally is supposed to advantage the producers of green electricity. However, due to the interplay of the emission constraints with the TGC market, this will not be the case despite the fact that, viewed in isolation, both systems work towards the same end of reducing carbon emissions. The reason for this lies in the specific construction of the TGC system. An increase of an emission permit price/ emission tax implies an upward shift of the marginal cost function for black electricity.[18] Recalling that the marginal cost function for electricity generated in the required proportion of green and black electricity is a linear combination of the marginal cost functions for green and black electricity, respectively, it follows immediately that the marginal cost function for electricity in the required proportion also must shift upwards. Consequently, in equilibrium, the end user price must be higher, consumption must be lower, and so must the generation of both green and black electricity in order to preserve the proportion given by the percentage requirement.

3. Trade in electricity only

In this section, we investigate how a TGC system functions in an open economy by expanding the model to include simultaneously functioning markets for electricity and TGCs in two countries, country A and country B. The variables involved are the same as those under autarky, but there is one set of variables for each country, denoted by subscript, $i = A, B$. In addition, we introduce the "trade variables", m and n, representing imports of electricity and TGCs, respectively. Demand may differ between

[17] In general, any positive shift of the marginal cost function for black electricity (e.g. resulting from an increase of input prices of black electricity generation) will induce a reduction in the generation of green electricity.

[18] Observe that, as the change of the emission permit price/ emission tax is exogenous in this model, there are no effects from the electricity market back to the permit market. Basically, what is happening is that the wholesale price will increase following from the increase of the emission permit price/ emission tax. However, due to substitution/altered mix within technologies considered black in the system, the wholesale price will not increase by as much as the permit price/ tax. In part, the increase of the wholesale price will stimulate generation of green electricity. However, the reduction of the TGC price more then offset the increase of the wholesale price, wherefore green electricity generation is reduced. Observe also that the substitution within the category of black technologies leaves black electricity "less black", but this is not considered green in the terminology of the system.

the two countries, but the demand functions have the same mathematical characteristics as the demand function in the previous section. Furthermore, we assume that the technologies applied in generating black and green electricity may differ between the two countries. This implies that comparative advantages and disadvantages may exist in the generation of black and green electricity of the countries. We assume that the cost functions for black and green electricity have the same mathematical characteristics as above.

3.1. First-order conditions and the equilibrium

First, we assume that cross-border trade takes place only for electricity, not for TGCs. Furthermore, for simplicity, we assume that there are no transaction costs involved and that there are no transmission constraints between the countries.[19] For these reasons, we can consider the electricity markets of countries A and B to be a single market with a common wholesale price; i.e., $q_A = q_B = q_M$. As there are only two countries involved, one country's imports must equal the other country's exports. Therefore, in equilibrium, it must be the case that $m_A^* = -m_B^*$. The equilibrium conditions for each of the markets in each of the countries can be expressed as follows:

6) $$p_i\left(x_i^*\right) = q_M^* + \alpha_i s_i^*;$$

7) $$x_i^* = y_i^* + z_i^* + m_i^* = \frac{z_i^*}{\alpha_i};$$

8) $$q_M^* + s_i^* = \frac{\partial h_i(z_i^*)}{\partial z_i};$$

9) $$q_M^* = \frac{\partial c_i(y_i^*, \tau)}{\partial y_i}.$$

Inserting 8) and 9) into 6), we find as under autarky:

10) $$p_i\left(x_i^*\right) = (1-\alpha_i)\frac{\partial c_i(y_i^*, \tau)}{\partial y_i} + \alpha_i \frac{\partial h_i(z_i^*)}{\partial z_i}, \quad i = A, B.$$

[19] This assumption is relaxed in the numerical model to follow.

3.2. *The effects of the percentage requirement*

In this section, we assume that the percentage requirement may be different between the two countries and focus on the effects of an increase in the percentage requirement in one of the countries, e.g. country A.

Taking the implicit derivate of 10) with respect to α_A, we find that the only signs that can be determined with certainty are those belonging to the effects on total combined black electricity generation for countries A and B, and the effects on country B's green electricity generation and electricity consumption. These effects follow from the expression below:

$$\frac{dY}{d\alpha_A} = \frac{\left\{(1-\alpha_A)s_A^* + x_A\left[\alpha_A \frac{\partial^2 h_A}{\partial z_A^2} - \frac{\partial p_A}{\partial x_A}\right]\right\}E_B}{D_A E_B + D_B E_A},$$

where $Y = y_A + y_B$, $D_i = \frac{\partial p_i}{\partial x_i} - (1-\alpha_i)^2 \frac{\partial^2 c_i}{\partial y_i^2} - \alpha_i^2 \frac{\partial^2 h_i}{\partial z_i^2} < 0$ and

$$E_i = \left[\alpha_i^2 \frac{\partial^2 h_i}{\partial z_i^2} - \frac{\partial p_i}{\partial x_i}\right]\frac{\partial^2 c_i}{\partial y_i^2}, \text{ for } i = A, B$$

Inspection of signs shows that the numerator is positive and the denominator negative. Hence, the effect on the aggregate generation of black electricity in the two countries is negative.

Furthermore, it can be shown that:[20]

$$sign\frac{dy_A}{d\alpha_A} = sign\frac{dy_B}{d\alpha_A} = sign\frac{dm_A}{d\alpha_A} = sign - \frac{dx_B}{d\alpha_A} = sign - \frac{dz_B}{d\alpha_A}.$$

As $\frac{\partial Y}{\partial \alpha_A} < 0$, it follows that $\frac{\partial y_A}{\partial \alpha_A} < 0$ and $\frac{\partial y_B}{\partial \alpha_A} < 0$. Furthermore, it must be the case that $\frac{dx_B}{d\alpha_A} > 0$ and $\frac{dz_B}{d\alpha_A} > 0$. In other words, somewhat surprisingly, the increase of the percentage requirement in country A leads to an increase in both electricity

[20] Proofs may be obtained from the authors upon request.

consumption and green electricity generation in country B while these effects are indeterminate for country A.[21]

In order to explain these effects, we first recall that an increase in the percentage requirement will necessarily lead to a reduction in the wholesale price of electricity. For country A, the effects on electricity generation and consumption are the same as those under autarky. However, in this two-country model with a common electricity market, the reduction of the wholesale price will imply that electricity becomes cheaper in country B, thus leading to increased demand in this country. However, in order to satisfy the percentage requirement, the demand for TGCs will have to increase in country B. As there is no trade in TGCs, the increase in demand for TGCs can only be satisfied by a corresponding increase of the TGC supply in country B. Hence, the generation of green electricity will have to increase in country B. Therefore, we arrive at the somewhat counterintuitive result that an increase of the percentage requirement in country A may lead to a reduction of green electricity generation in country A, but will definitely lead to an increase of green electricity in country B.

3.3. The effects of the emission permit price/emission tax

In this case an increase of the carbon emission permit price/ carbon tax implies a reduction of green electricity generation in both countries, i.e. $\frac{dz_A}{d\tau} < 0$ and $\frac{dz_B}{d\tau} < 0$, a reduction of total generation of black electricity, i.e. $\frac{\partial Y}{\partial \tau} < 0$, and a corresponding increase of the wholesale price, i.e. $\frac{\partial q_M}{\partial \tau} < 0$. (Proof is given in Appendix A). The intuition behind these results is the same as the intuition for the autarky case.

4. Trade in both electricity and TGCs

In this section both electricity and TGCs are traded. This implies that both the wholesale price of electricity and the price of TGCs are common for the countries.

[21] From a numerical model satisfying the assumptions of this paper, it can be shown that equilibria exist where the green electricity generation and electricity consumption in country A may either increase or decrease following an increase in the percentage requirement in country A. The details of this proof are not included in the paper, but may be obtained from the authors upon request.

Hence, s_A and s_B are replaced by s_M in the objective functions and first-order conditions below. Otherwise, the model specification is as in the previous case.

4.1. First-order conditions and equilibrium

TGCs will be imported if the domestic demand for certificates exceeds the domestic supply. In equilibrium, the imports of one country will be equivalent to the exports of the other country; i.e. $n_A^* = -n_B^*$. The trade in TGCs implies that the relative share of green electricity generated in one country may be different from the percentage requirement. The equilibrium can be expressed as follows:

11) $$p_i\left(x_i^*\right) = q_M^* + \alpha_i s_M^*;$$

12) $$x_i^* = y_i^* + z_i^* + m_i^* = \frac{z_i^* + n_i^*}{\alpha_i};$$

13) $$q_M^* + s_M^* = \frac{\partial h_i(z_i^*)}{\partial z_i};$$

14) $$q_M^* = \frac{\partial c_i(y_i^*, \tau)}{\partial y_i}.$$

Inserting 13) and 14) into 11), we find again.

15) $$p_i\left(x_i^*\right) = (1-\alpha_i)\frac{\partial c_i(y_i^*, \tau)}{\partial y_i} + \alpha_i \frac{\partial h_i(z_i^*)}{\partial z_i}, \quad i = A, B.$$

4.2. The effects of the percentage requirement

The analysis shows that it is possible to determine only the effect on black electricity generation of an increase in the percentage requirement. Again, this effect is negative i.e. $\frac{dY}{d\alpha_A} < 0$. To realize this, assume the opposite i.e. $\frac{dY}{d\alpha_A} \geq 0$. This implies an increase in green electricity generation in order to fulfill the percentage requirement in both countries. Hence, in equilibrium, the consumption of green electricity must increase in both countries, as we now have a common market for both electricity and TGCs. Constant or increased generation of black electricity implies that the wholesale price, q_M, is constant or increases, respectively. Furthermore, for the generation of green electricity to increase, the price of green electricity, $q_M + s_M$, must increase. From 11), this implies an increase in the end-user price of electricity in both countries. This is not compatible with an increase in the consumption of electricity. Thus, we have a contradiction, which leads to the result that $\frac{dY}{d\alpha_A} < 0$. Furthermore, as in the case of trade in electricity only, it can be shown that $sign\frac{dy_A}{d\alpha_A} = sign\frac{dy_B}{d\alpha_A}$. Hence, we must have $\frac{dy_A}{d\alpha_A} < 0$ and $\frac{dy_B}{d\alpha_A} < 0$.

Furthermore, the analysis shows that the effect on total green electricity generation of increasing the percentage requirement in country A is indeterminate. As we now have a common market for TGCs, it can be shown that: $sign\frac{dz_A}{d\alpha_A} = sign\frac{dz_B}{d\alpha_A}$. Thus, in contrast to the case of trade in electricity only, an additional opportunity for trading TGCs implies that we no longer obtain the unambiguous result that an increase of α_A leads to an increase in green electricity generation in country B. The change in green electricity generation must now occur in the same direction in both countries.[22] Finally, the results show that the effect on electricity consumption is indeterminate in both countries.

4.3. The effects of the emission permit price/ emission tax

In this case, increased emission permit price/emission tax implies a reduction of green electricity generation in both countries i.e. $\frac{dz_A}{d\tau} < 0$ and $\frac{dz_B}{d\tau} < 0$, a reduction of total generation of black electricity, i.e. $\frac{\partial Y}{\partial \tau} < 0$, and a corresponding increase of the wholesale price, i.e. $\frac{\partial q_M}{\partial \tau} < 0$. (Proof is given in Appendix A). The intuition behind these results is the same as the intuition for the autarky case.

[22] Proofs may be obtained from the authors upon request.

5. Numerical analysis and discussion

The results from the analytical model investigated above are somewhat discouraging. Indeed, as can be seen from Table 1 that summarizes the results, not very much can be said about the effects of increasing the percentage requirement that is the main policy instrument of the TGC system. In fact, with trade in both electricity and TGCs the only clear cut result is that the generation of black electricity will be reduced in the participating countries, and there is no guarantee that generation of green electricity will be stimulated. Also, nothing precise can be said about the effect on total electricity generation. However, an increase of the emission permit price/emission tax will definitely *reduce* green electricity generation which may seem somewhat surprising. In view of these results it may be of some interest to investigate how the TGC system will function when applied to a real world case. For that purpose we apply a partial equilibrium model for Norway and Sweden using realistic parameter values.

Table1. Effects of the percentage requirement (α) and of the emission permit price/emission tax (τ)

	$\frac{dz_A}{d\alpha_A}$	$\frac{dz_B}{d\alpha_A}$	$\frac{dy_A}{d\alpha_A}$	$\frac{dy_B}{d\alpha_A}$	$\frac{dx_A}{d\alpha_A}$	$\frac{dx_B}{d\alpha_A}$	$\frac{dz_A}{d\tau}$	$\frac{dz_B}{d\tau}$
Autarky	?		-		?		-	
Trade in electricity only	?	+	-	-	?	+	-	-
Trade in electricity and TGCs	?	?	-	-	?	?	-	-

The model is based on the principles of the analytical model developed above and is designed to take care of trade in both electricity and TGCs between the two countries in 2010.[23] It determines equilibrium prices and quantities on, and cross border tariffs between, the electricity markets as well as equilibrium prices and trade on the markets for TGCs in Norway and Sweden. Basic features of the model are described in Appendix B.

[23] The basic model is developed by Lars Bergman, Stockholm School of Economics and applied in e.g. Andersson and Bergman (1995) and Amundsen and Bergman (2002). The TGC part was included in the model for Sweden by Bergman and Radetzki (2003) and further updated and expanded for the present purpose. Detailed information on data can be obtained from the authors upon request.

First we consider the effects of introducing a TGC system with a percentage requirement of 5% for Norway and 12.7% for Sweden.[24] Thereafter we consider the effects of changing the carbon emission tax. We follow the general structure of the analytical part of the paper and consider three scenarios for each of these two cases: i) Autarky, ii) Trade of electricity only and iii) Trade in electricity and TGCs.

5.1 The effects of introducing a TGC system

The effects of introducing a TGC system for Norway are summarized in Table 2. Technically this has been achieved by increasing the percentage requirement from zero to 5%.

Table 2. Effects of introducing a TGC market for Norway. Figures in TWh and EUR[25]/MWh

α	z	y	x	q	s	p
0	0.8	130.5	131.3	26.38	0	26.38
0.05	6.7	127.6	134.3	23.22	24.14	24.42

As can be seen from Table 2, we have the expected effects of reduced wholesale price of electricity and reduced generation of black electricity. Also, there is an increase of green electricity as well as of total electricity generated and a reduction of the end user price. Basically what is happening in this case is that revenues (hydro rents) are transferred from hydro power producers as subsidies to the producers using new green generation capacity. Hence, for this numerical case, the indeterminate effects on green electricity generation and total electricity consumption from the analytical model have been determined.

Table 3 displays the effects of introducing TGC markets in both countries but allowing for trade in electricity only. The Table shows three features. Firstly, it shows that the effects of introducing a TGC market in Sweden are similar to those in Norway.

[24] For Sweden this percentage corresponds to the escalation plan for 2010. For Norway a percentage requirement of 5% has been proposed but not decided.

[25] Swedish kronor (SEK) has been converted to Euro by using the 2005 average exchange rate of 9.29 per EUR.

Table 3. Effects of introducing TGC markets for Norway and Sweden with trade in electricity only. Figures in TWh and EUR/MWh

α_N	α_S	z_N	z_S	y_N	y_S	x_N	x_S	q_N	q_S	s_N	s_S	p_N	p_S
0	0	0.8	1.3	129.0	171.0	131.1	171.0	25.86	25.83	0	0	25.86	25.83
0	0.127	0.8	21.3	127.4	164.5	134.1	168.0	24.57	24.48	0	22.88	24.57	27.38
0.05	0.127	6.8	21.9	127.4	164.5	136.3	172.3	22.00	21.98	25.36	25.38	23.27	25.20
0.10	0.127	10.3	22.0	106.1	150.6	103.5	173.2	13.24	8.61	497.42	90.57	62.98	20.12

Secondly, Table 3 shows the effects of introducing a TGC market in Norway in addition to that in Sweden. In this case the generation of green electricity as well as total electricity consumption increase in both countries. Furthermore, the wholesale prices fall in both countries but due to the assumed stepwise linear marginal cost functions the generation of black electricity is not affected in any of the countries. Thirdly, Table 3 shows what is happening as the percentage requirement increases in Norway (from 5 to 10 percent) but remains the same in Sweden. One effect of this change is a reduction of black electricity generated in each of the countries and a corresponding reduction of wholesale prices (that are not completely equalized due to transmission constraints). Also we see that the generation of green electricity increases. This is as expected for Sweden according to the analytical model. However, even the green electricity generation in Norway increases. This effect was indeterminate in the analytical model. Furthermore, it turns out that total electricity consumption falls in Norway while it increases in Sweden. Also, Table 3 shows that this change has very strong effects on the TGC prices and end user prices in both countries.

Table 4 displays the effects of introducing TGC markets in Norway and Sweden and allowing for trade in both electricity and TGCs. We observe that the generation of green electricity is increased in both countries. In Norway the increase is larger in the case of a common TGC system between Norway and Sweden, than in the case of separate TGC systems. In both the cases, the generation of black electricity is reduced. This reflects a competitive advantage for generation of green electricity in Norway. Thus, TGCs are exported from Norway to Sweden. As expected, Norway and Sweden get identical TGC prices in the common TGC system.

Table 4. Effects of introducing TGC markets for Norway and Sweden with trade in both electricity and TGCs. Figures in TWh and EUR/MWh

α_N	α_S	z_N	z_S	y_N	y_S	x_N	x_S	q_N	q_S	s_N	s_S	p_N	p_S	z_{NS} *
0	0	0.8	1.3	129.0	171.0	132.1	171.0	25.86	25.83	0	0	25.86	25.83	0
0	0,127	0.8	20.1	127.4	164.7	133.8	167.6	24.78	24.75	0	22.62	24.78	27.62	0.8
0,05	0,127	10.3	17.9	127.4	164.5	136.3	172.3	22.00	21.98	25.38	25.38	23.27	25.20	3.6
0,10	0,127	10.34	22.2	127.4	134.1	125.8	155.6	11.83	1184	185.37	185.37	30.37	35.38	1.0

* This variable reflects the net export of TGCs from Norway to Sweden

The last row of Table 4 illustrates a situation in which Norway increases its percentage requirement from 5 to 10 per cent, while Sweden continues on 12.7 per cent. In accordance with the theoretical results we note that the positive effect on the generation of green electricity is significantly stronger in Sweden than in Norway, even as the Swedish percentage requirement is unchanged, while the Norwegian percentage requirement is increased. In this case, the consumption of electricity is, however, reduced in both countries.

5.2 The effects of the emission permit price/ emission tax

From Table 5 we see that the effects of increasing the emission permit price/ emission tax for Norway under autarky are rather small. The reason is that electricity in Norway is mostly generated from hydro which causes no carbon emissions. However, as can be seen from Table 5, the wholesale price of electricity increases, thus leading to a little less black electricity generated. Otherwise, there is no noticeable effect on green electricity generation, but the price of TGCs falls in accordance with the analytical results.

Table 5. Effects of changing the emission permit price/ emission tax for Norway under autarky. Figures in TWh and EUR/MWh

τ	z	y	x	q	s	p
0	6.7	127.6	134.3	23.22	24.14	24.42
4,2	6.7	127.4	134.1	23.25	24.11	24.46
8,4	6.7	127.4	134.1	23.26	24.10	24.47

Table 6 displays the effects of increasing the emission permit price/ emission tax for Norway and Sweden with trade in electricity only. Again, the effects of changing the carbon tax are relatively modest as both Norway and Sweden have little emission of carbon in electricity generation. Sweden does, however, have some generation coming from combined heat and power plants. This appears to be the marginal technology for generation of black electricity in the simulations. Thus, this is the reason why the generation of black electricity in Sweden is reduced as the emission permit price/ emission tax is increased, while Norway is not affected at all. Furthermore, we notice that raising the emission permit price/ emission tax leads to a higher wholesale price of electricity and a lower TGC-price. Our result from the theoretical analysis thus seems to be confirmed by the numerical simulations, i.e. increasing the emission permit price/ emission tax in a system which also includes TGCs may have an adverse effect on the generation of green electricity; although, the effect is not very strong.

Table 6. Effects of changing the emission permit price/ emission tax for Norway and Sweden with trade in electricity only. Figures in TWh and EUR/MWh

τ	z_N	z_S	y_N	y_S	x_N	x_S	q_N	q_S	s_N	s_S	p_N	p_S
0	6.8	21.9	127.4	164.5	136.3	172.3	22.00	21.98	25.36	25.38	23.27	25.20
4,2	6.8	21.8	127.4	163.5	135.8	171.7	22.31	22.28	25.06	25.08	23.55	25.47
8,4	6.8	21.1	127.4	162.6	135.2	171.1	22.66	22.64	24.70	24.73	23.90	27.85

Finally, Table 7 shows the effects of changing the emission permit price/ emission tax for Norway and Sweden with trade both in electricity and TGCs. We notice that opening of trade in TGCs does not affect the results, other than for the domestic generation of green electricity. The effects of changing the emission permit price/ emission tax are similar to the case in which only electricity is traded.

Table 7. Effects of changing the emission permit price/ emission tax for Norway and Sweden with trade both in electricity and TGCs. Figures in TWh and EUR/MWh

τ	z_N	z_S	y_N	y_S	x_N	x_S	q_N	q_S	s_N	s_S	p_N	p_S	z_{NS} *
0	10.3	17.9	127.4	164.5	136.3	172.3	22.00	21.98	25.38	25.38	23.27	25.20	3.6
4,2	10.3	17.8	127.4	163.5	135.8	171.7	22.30	22.28	25.08	25.08	23.56	25.47	3.6
8,4	10.3	17.6	127.4	162.6	135.2	171.1	22.65	22.63	24.74	24.74	23.89	25.77	3.7

6. Summary and concluding remarks

The main objective of this paper is to investigate the analytics of a TGC system of the Nordic type when integrated within several countries and try to determine what can be expected from the system when applied in a real world setting. In particular, we ask whether it is possible to derive analytically clear-cut results with respect to how the system affects generation of electricity from renewable resources, and from carbon emitting resources, in the same way as it is possible for other known policy instruments such as an emission permit system or a plain carbon emission tax. In particular, the paper addresses the role of policy measures in TGC markets, the integration of country-specific TGC markets, and compatibility issues between TGC markets and an emission permit system/ emission tax system. Both an analytical model and a partial equilibrium model for Norway and Sweden are applied.

One of the main conclusions of this paper is that the percentage requirement is not a very precise policy measure for stimulating green electricity generation. Thus, an increase of the percentage requirement will not necessarily lead to an increase of green electricity generation in the long run, though it will lead to less generation of black electricity. It guarantees only an increase in green electricity's *share* of total consumption. These results are shown to be valid for all the cases investigated; i.e., under autarky and when electricity, or both electricity and TGCs, are traded between two countries. However, it should be noted that a larger percentage requirement may be compatible with more green electricity generation over time if there is a general increase of demand. Still, the immediate effect of a higher percentage requirement on green electricity generation cannot be guaranteed.[26] Hence, if the objective is to achieve a given target of new green generation capacity, a TGC system may not be the best system to use. Other systems, such as a tendering or auction system, or a system of plain subsidies, may work better in this respect. On the other hand, the TGC system does provide a strong role for market forces and do take account of consumers' willingness to pay for electricity via the effects on demand and the end-user price. In

[26] Moreover, the percentage requirement for a single country is not a very potent measure if the country in question is part of a large internationally integrated system of competitive markets for electricity and TGCs. Such a circumstance would imply that the prices of electricity and TGCs are given, and that the electricity producers and the retailing companies in the economy will adapt to these prices. However, this in turn implies that neither the percentage requirement nor the TGC price bounds for a given country can be used to influence the green electricity generation or the composition of green and black electricity in that country.

addition, the TGC system allows for voluntary purchases of TGCs by consumers who wish to support green electricity generation.[27]

Furthermore, as both the theoretical and numerical analysis show, an increase of the percentage requirement will have an indeterminate effect on total electricity consumption under autarky. Also, in the case where one country implements a TGC system and trades electricity with another country, the effect of an increase of the percentage requirement on total consumption will be indeterminate in the country implementing the TGC system. However, as confirmed in the numerical analysis, the other country will experience an increase in both the total electricity consumption and green electricity generation. Still, allowing for trade of TGCs between the countries leads to an indeterminate effect on both these variables in the country that does not implement the TGC system.

Another main conclusion of the paper is that an increase of an emission permit price/ emission tax will push the price of TGCs downwards, lowering the profits of the green electricity producers and thus lead to a reduction of green electricity generation. This result was shown to be valid in all specified cases as well as in the partial equilibrium model. This also raises the question as to why two policy measures are needed to achieve what seems to be a common goal (i.e. emission reduction), as in the case of the European ETS and TGC systems. Presumably, the answer is that the aims of the two systems are somewhat different. The ETS system is targeted at reducing global emissions of carbon and says nothing about that this must be achieved through increased generation of green electricity. The TGC system, on the other hand, is targeted directly at achieving an electricity supply from renewable sources. Clearly, the TGC system may achieve a reduction of carbon emissions, but it also reduces the use of nonrenewable sources, notably crude oil and natural gas, that are in scarce supply and used at the expense of future generations.

Additional problems associated with the TGC systems need to be resolved. One problem relates to TGC price volatility. If the green generation technologies in a country largely consist of wind or water power, sizable and erratic variations of green

[27] The option of buying green electricity at a surcharge has been offered in many countries, for instance Vattenfall in Sweden. However, demand has been low.

electricity generation may occur, owing to natural annual variations of wind or precipitation. Therefore, there may be similar variations in the numbers of TGCs for sale. This in turn will give rise to a high volatility of TGCs prices. Hence, potential investors in green electricity capacity face a highly uncertain rate of return on their investments and therefore require high expected rates of return to be willing to invest. To some extent, however, the problem of price volatility may be resolved by the introduction of permit banking (see Amundsen et al., 2006).

Another problem related to the TGC market is the potentially high market power that a producer of green electricity may possess. The reason for this is that the percentage requirement implies that one TGC counts for a multiple of MWh in consumption. Hence, by withholding TGCs, a green producer may significantly reduce consumption and increase the end-user price, even though the producer's own power generation is not that large.

Along with the other potential problems discussed above, the problems revealed in this paper clearly call for caution in the design and implementation of TGC systems, not least when they are put into place on top of emission trading systems.

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Appendix A

i) Proof of the effects of the emission permit price/emission tax as there is trade in electricity only

To verify that $\frac{dz_A}{d\tau} < 0$ and $\frac{dz_B}{d\tau} < 0$, rearrange 10) to obtain:

$$p_i\left(x_i^*\right) = \left(1-\alpha_i\right)q_M + \alpha_i \frac{\partial h_i(z_i^*)}{\partial z_i}.$$

which upon differentiation gives:

$$\text{A1)}\quad \frac{\partial p_i}{\partial x_i}\frac{dx_i}{d\tau} - \alpha_i \frac{\partial^2 h_i}{\partial z_i^{\,2}}\frac{dz_i}{d\tau} = (1-\alpha_i)\frac{dq_M}{d\tau} \quad , \; i = A, B.$$

From 7), we have $z_i = \alpha_i x_i$. Therefore, we may write:

A2) $$\frac{1}{1-\alpha_A}\left(\frac{\partial p_A}{\partial x_A}\frac{1}{\alpha_A}-\alpha_A\frac{\partial^2 h_A}{\partial z_A{}^2}\right)\frac{dz_A}{d\tau}=\frac{dq_M}{d\tau}=\frac{1}{1-\alpha_B}\left(\frac{\partial p_B}{\partial x_B}\frac{1}{\alpha_B}-\alpha_B\frac{\partial^2 h_B}{\partial z_B{}^2}\right)\frac{dz_B}{d\tau}.$$

To prove the above claim by contradiction, assume $\frac{dz_A}{d\tau}\geq 0$. Inspecting the signs of A2), we see that this implies $\frac{dz_B}{d\tau}\geq 0$, $\frac{dx_A}{d\tau}\geq 0$, $\frac{dx_B}{d\tau}\geq 0$, and $\frac{dq_M}{d\tau}\leq 0$. From 9), we see that $\frac{dq_M}{d\tau}\leq 0$ implies $\frac{dy_A}{d\tau}<0$ and $\frac{dy_B}{d\tau}<0$. Upon applying 7) and eliminating m_i, we find:

A3) $$\left(1-\alpha_A\right)\frac{dx_A}{d\tau}+\left(1-\alpha_B\right)\frac{dx_B}{d\tau}=\frac{dy_A}{d\tau}+\frac{dy_B}{d\tau}.$$

Inspection of the signs of A3) reveals that the left-hand side is nonnegative, whereas the right-hand side is negative. Hence, there is a contradiction. Therefore, it follows that the generation of green electricity and the consumption of electricity must fall in both countries. Furthermore, from A3), it is apparent that the total generation of black electricity must be reduced, whereas A2) makes it clear that the wholesale price of electricity will have to go up.

ii) Proof of the effects of the emission permit price/emission tax as there is trade in both electricity and TGCs

To verify that $\frac{dz_A}{d\tau}<0$ and $\frac{dz_B}{d\tau}<0$ first observe from 12) that:

A4) $$\alpha_A\frac{dx_A}{d\tau}+\alpha_B\frac{dx_B}{d\tau}=\frac{dz_A}{d\tau}+\frac{dz_B}{d\tau}$$ and

A5) $$(1-\alpha_A)\frac{dx_A}{d\tau}+(1-\alpha_B)\frac{dx_B}{d\tau}=\frac{dy_A}{d\tau}+\frac{dy_B}{d\tau}.$$

To prove the above claim by contradiction, assume that the generation of green electricity in country A is not reduced; i.e. $\frac{dz_A}{d\tau}\geq 0$. From 13), it follows that if one country does not reduce green electricity generation, this implies that the *other* country will not reduce its green electricity generation either. This must be the case as both countries are subject to the same change in $q_M + s_M$. From A4), we observe that this means that the consumption of electricity in at least *one* of the countries must either increase or remain constant. Assume that country A does not reduce its consumption of electricity; i.e., $\frac{dx_A}{d\tau} \geq 0$ Differentiating 15) in the same way that we found A2), we find:

A6) $$\frac{1}{1-\alpha_A}\left(\frac{\partial p_A}{\partial x_A}\frac{dx_A}{d\tau} - \alpha_A \frac{\partial^2 h_A}{\partial z_A{}^2}\frac{dz_A}{d\tau}\right) = \frac{dq_M}{d\beta} = \frac{1}{1-\alpha_B}\left(\frac{\partial p_B}{\partial x_B}\frac{dx_B}{d\tau} - \alpha_B \frac{\partial^2 h_B}{\partial z_B{}^2}\frac{dz_B}{d\tau}\right).$$

As $\frac{dz_A}{d\tau} \geq 0$ and $\frac{dx_A}{d\tau} \geq 0$, we observe from A6) that $\frac{dq_M}{d\tau} \leq 0$, which implies $\frac{dy_A}{d\tau} < 0$ and $\frac{dy_B}{d\tau} < 0$. Therefore, the right-hand side of A5) is negative, whereas the right-hand side of A4) is nonnegative. For this to happen, we must have $\frac{dx_B}{d\tau} < 0$ and in addition $\alpha_A > \alpha_B$. As we have assumed that green electricity generation does not decline and we have $\frac{dq_M}{d\tau} \leq 0$, it follows that $\frac{ds_M}{d\tau} \geq 0$. From A2), we see that for green electricity generation to decrease in country A, we must have $\alpha_A < \alpha_B$. This contradicts that $\alpha_A > \alpha_B$. Hence, the conclusion is that green electricity generation will be reduced in both countries.

Appendix B: *Some basic features of the partial equilibrium model*

The model applied depicts the behavior of individual power producing firms on the Norwegian – Swedish electricity market. In addition there is an independent grid operator that owns and operates an inter-connector between the two countries. The flow of power across the national border is constrained by transmission capacity. Each firm, f_d has a country location, d and operates a set of generating units, all located in the home country. Firms may be of different sizes, and may have different "portfolios" of generating units. These are divided into three categories, i, j and g. Category i consists of existing hydro-, existing nuclear- and existing wind power plants. Category j consists of condensing and combined heat (CHP) power plants and category g consists of new hydro-, new wind, and bio power plants. Categories i, j are considered "black", whereas g is considered "green"[28]. Quantities produced in categories i, j, g and total quantity produced in firm f_d are denoted $Y_{f_d i}$ $Y_{f_d j}$ $Z_{f_d g}$ and X_{f_d}, respectively. Hence, $X_{f_d} = \sum_1^3 Y_{f_d i} + \sum_1^2 Y_{f_d j} + \sum_1^3 Z_{f_d g}$.

Cost functions

For each given level of output the individual firm allocates production between the different generating units in order to minimize cost. The solution of this cost minimization problem defines the cost function of the individual firm. Hydro-, nuclear-, wind- and bio power plants are assumed to be homogenous, i.e., for each type of plant the marginal cost is independent of the level of capacity utilization and equal to c_i, (for existing hydro-, existing nuclear- and existing wind power), and h_g, (for new hydro-, new wind- and bio power). The total available capacity in plants of type i, j and g in firm f_d are denoted $K_{f_d i}, K_{f_d j}$ and $K_{f_d g}$, respectively.

Condensing and CHP generating units are assumed to be heterogeneous (due to differing fuel input and thermal efficiency). Heterogeneity is reflected in the marginal cost function of condensing and CHP plants, respectively. These functions are written

$$C_{f_d j} = a_j + b_j \left(\frac{Y_{f_d j}}{K_{f_d j}} \right)^{\rho}$$

Here, a_j represents the marginal cost of the least expensive unit of type j, while $a_j + b_j$ represents the marginal cost of operating the most expensive generating unit of type j close to full capacity. Furthermore, ρ is a (positive) technological parameter. All parameters are estimated on the basis of engineering data, whereas capacity data are obtained from published reports.

The solution to the cost minimization problem is captured in the marginal cost function denoted $C_{f_d} = C_{f_d}(X_{f_d}, K_{f_d i}, K_{f_d j}, K_{f_d g})$. The function includes a tax on carbon emission and takes into account that the net cost of generating a unit of green electricity is equal to $h_g - s_d$, where s_d is the TGC price.

[28] This is according to governmental decisions. Hence, for Norway "black" electricity generation is almost exclusively taking place in water power plants whereas black electricity generation in Sweden also includes electricity from nuclear-, gas- and coal power plants.

Demand function

The demand for electricity by consumers in country r, E_r, depends only on the area price, P_r. The price elasticity of demand in country r is denoted η_r and is assumed to be constant. Thus, the inverse demand function for consumers in country r becomes

$$P_r = P_r^0 (\frac{E_r}{E_r^0})^{\frac{1}{\eta_r}}$$

Where P_r^0 is the base year price and E_r^0 the base year consumption in country r.

Equilibrium on the electricity market

The spatial allocation of generation and consumption, in conjunction with inter-connector capacity limitations[29], makes it important to distinguish between the amount of electricity generated and the amount of electricity supplied in different regions by a given firm. Letting Q denote supply we thus have $X_{f_d} = \sum_r Q_{f_{dr}}$. The total supply of power in country r, Q_r is defined by $Q_r = \sum_d \sum_{f_d} Q_{f_d r}$. In equilibrium it holds that $Q_r = E_r$. When the inter-connector capacity is not congested (or in autarky) there is a single equilibrium price, otherwise not.

Equilibrium on the TGC market

The demand for TGCs in country r is equal to $\alpha_r E_r$ where α_r is the percentage requirement. The generation of TGCs by firm f_d is equal to $Z_{f_d g}$. Denoting supply of TGCs by $N_{f_{dr}}$ we have $Z_{f_d g} = \sum_r N_{f_{dr}}$. The total supply of TGCs in country r, N_r is defined by $N_r = \sum_d \sum_{f_d} N_{f_d r}$. In equilibrium it holds that $N_r = \alpha_r E_r$. With a common TGC market, a single TGC price, s_r is established, otherwise separate TGC prices are established.

[29] To save space the transmission part of the model is not discussed.