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**Integrated Tradable Green Certificate
Markets: Functioning and Compatibility**

by

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Integrated Tradable Green Certificate Markets: Functioning and Compatibility

by

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Abstract:

Many countries plan to increase the proportion of their electricity supply obtained from renewable sources relative to nonrenewable sources. Recently, the EU has implemented a system of tradable emission permits and many countries have introduced systems of tradable green certificates (TGCs). In this paper, we analyze how integrated TGC markets function and how they are affected by harsher CO₂ emission constraints. A key result of our analytical model is that TGCs may be an imprecise instrument for regulating the generation of green electricity. Furthermore, our analysis shows that the combination of TGCs with a system of tradable emission permits may yield outcomes contrary to the intended purpose. The results are valid under both autarky and international trade.

JEL classifications: C7; Q28; Q42; Q48

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

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1. Introduction³

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 TGC system called the *UK Renewables Obligation Certificate (ROC) Market*. Sweden introduced its system in 2003. The Norwegian Parliament has decided that Norway will introduce a TGC system on January 1, 2006. The plan is that Norway and Sweden will start trading TGCs from this date onwards, creating the first integrated TGC

³ Financial support from SNF's Energy Research Program (financed by Gassco, Statkraft, Statnett and Statoil), the Norwegian Research Council (SAMSTEMT), and the Nordic Energy Research Program (NEMIEC) is gratefully acknowledged.

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>).

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 perform⁷ when it expands to include several countries.

Along with the development of the TGC markets in Europe, a more general and comprehensive system of CO₂ 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 the cost of using a CO₂-emitting resource, the cost increment being in proportion to the emissions per unit of the resource used. As a result, input substitution is expected to take place in electricity generation, away from coal and gas power towards hydro, wind, and nuclear power. 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. An essential issue dealt with in this paper is the compatibility of the TGC and ETS systems, with particular emphasis on how harsher CO₂ emission constraints affect the generation of green electricity within the setting of a TGC market.

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

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 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 will be put into effect in 2005. At first, it will comprise only CO₂ emissions, but other greenhouse gases will be included later. The system covers emissions from several sectors, including electricity and district heating.

percentage of the total end use demand for electricity. Based on supply and demand, a single TGC price is established between administratively set upper and lower price bounds.

The TGC markets are based on two policy measures that the government uses to influence the role of green electricity in the power market; these are the percentage requirement and the upper and lower price bounds for the TGC price. The percentage requirement is particularly important, but the price bounds may also play a significant role.⁹ Both Sweden and the UK have specific plans to increase their percentage requirements. Thus, the percentage requirement is viewed as a means of attaining specific targets for green electricity. Amundsen and Mortensen (2001) investigated aspects of these policy measures for domestic TGC and electricity markets. TGC price volatility and banking were dealt with by Amundsen et al. (2004), whereas market power issues were addressed in Amundsen and Nese (2002). Furthermore, numerical models of TGC and electricity markets for specific regions and settings have been formulated and analyzed (e.g., Bergman and Radetzki, 2003; Bye 2003; Hindsberger et al., 2003; Nese, 2003).

As mentioned above, the main problems investigated in this paper relate to the integration of TGC markets and how these markets are affected by acting in concert with a CO₂ permits market, such as the emerging European ETS system. To some extent, problems of compatibility 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 the effects of the major policy measure, the percentage requirement. Seemingly paradoxical results are derived from the analysis, such as the finding that an increase of the percentage requirement in one country may lead to less green electricity generation in this country, but more green electricity generation in another country. Another example is the result that a harsher emission constraint in the CO₂ emission permits market may actually lead to less green electricity generation when TGC markets are involved. Such results will be derived and explained

Although the questions we pose are simple, it is not so easy to derive both general and precise answers. Consequently, a formal approach is required, and we formulate an analytical model

⁹ On the significance of price bounds, see, for example, Amundsen and Nese (2002). We will not deal with the importance of price bounds in this paper.

with general assumptions; e.g., for demand and cost functions. From this model, we derive and prove specific results.

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 an increase of the percentage requirement in one of the participating countries, or by harsher CO₂ emission constraints. 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. However, even in such a case, changes in the TGC market of one country may influence the TGC market of another country, as well as the common electricity market. Therefore, we proceed to analyze cases involving both a common TGC market and a common electricity market. Finally, we discuss the 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 in a long-run setting 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

α = Green electricity required as a proportion of total electricity consumption ("percentage requirement")

β = Emission constraint on CO₂

g^d = Demand for TGCs

g^s = Supply of TGCs

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

$c = c(y; \beta)$: Industry cost function¹⁰ for black electricity with emission constraints.¹¹ We

assume $\frac{\partial c}{\partial y} > 0$, $\frac{\partial^2 c}{\partial y^2} \geq 0$, and $\frac{\partial^2 c}{\partial y \partial \beta} > 0$. The case where $\beta = 0$ signifies that there are no emission constraints.

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

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

2.1. First-order conditions and the equilibrium

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 black and green electricity, many retailers, and many end users of electricity. Hence, all agents treat the various prices as given by the market.

The producers act as if they jointly maximize:

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

The first-order condition for black electricity generation is:

$$q = \frac{\partial c(y, \beta)}{\partial y}.$$

¹⁰ 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).

¹¹ The cost function for black electricity conditional on CO₂ emission constraints may be derived from a standard cost minimization problem, with the addition of a CO₂ emission constraint. This function explicitly takes into account the fact that suppliers may continue to generate a given quantity of electricity even if the emission constraint is made harsher. This is possible if suppliers use cleaner fuels and cleaner generation technologies. However, such a substitution implies increased generation costs, which shift the cost curve upwards compared with its position before the introduction of firmer emission constraints.

The first-order condition for green electricity generation is:

$$q + s = \frac{\partial h(z)}{\partial z}.$$

For each unit of electricity (i.e., each 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. For simplicity, electricity distribution is assumed to be costless. With a large number of retailers, the equilibrium established in the market (i.e., the competitive equilibrium) must be characterized by:

$$p = q + \alpha s \quad .$$

We assume that the amount of TGCs is measured in the same units as the amount of green electricity. Thus, the demand for TGCs is given by $g^d = \alpha x$ and the supply of TGCs is given by $g^s = z$.

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

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

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

$$3) \quad q^* = \frac{\partial c(y^*, \beta)}{\partial y} ;$$

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

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:

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

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

2.2. The effects of the percentage requirement as a means for promoting green electricity generation

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 consumption may well increase even if green electricity generation declines, if there is a sufficient reduction of electricity consumption and of black electricity generation. However, an increase in the percentage requirement will definitely lead to a reduction of black electricity generation and, therefore, a reduction in the wholesale price of electricity (see condition 3). As the effect on the generation of green electricity is indeterminate, the effects on total electricity generation and consumption, as well as the end-user price, are also indeterminate.

In the following section, we study these effects in more detail.¹² To examine the effect of an increase in the percentage requirement (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 derivatives. Hence, omitting the starred symbols for the sake of simplicity, we obtain:

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

where

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

¹² The results in this paragraph represent a generalization of those obtained by Amundsen and Mortensen (2001, 2002).

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.

In the same way, we obtain an equation representing the effect of an increase in the percentage requirement on black electricity generation:

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

An inspection of the 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:

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

An inspection of the 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 find 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 .¹³ 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 *is* true that it will lead to a

¹³ 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) and Jensen and Skytte (2002).

reduction of black electricity. Furthermore, it is not obvious how total electricity generation is affected.

2.3. The effects of harsher CO₂ emission constraints

In order to investigate the equilibrium effect of harsher CO₂ emission constraints on green electricity, we take the implicit derivate of expression 5) with respect to β . Hence, we obtain:

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

With the assumed cross effects of the marginal cost function of black electricity it follows that the numerator is positive while the denominator is negative. Therefore, the total effect is negative. Hence, harsher CO₂ emission constraints will *not* lead to an increase in the generation of green electricity. On the contrary, generation of green electricity will decline.¹⁴ Owing to the fact that $z^* = \alpha x^* = \alpha(1-\alpha)y^*$, both the generation of black electricity and the total consumption will be reduced as the CO₂ emission constraint becomes harsher. Furthermore, we see from expression 4) that a reduction in the generation of green electricity implies that the sum of the wholesale price and the TGC price must fall. However, it is not necessarily true that both the wholesale price and the TGC price fall.

It may seem paradoxical that harsher CO₂ emission constraints can actually lead to a reduction in the generation of green electricity. Harsher emission constraints imply an increase in the price of emission permits, which is supposed to advantage the producers of green electricity. However, owing 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, a reduction of CO₂ emissions. The reason for this lies in the specific construction of the TGC system. Harsher CO₂ constraints imply an increase in the price of emission permits and an increase in the wholesale price of electricity. Within the TGC system, this implies that the TGC price is reduced by more than the increase in the wholesale price (depending on the size of the percentage requirement), so that the sum of the TGC price

¹⁴ In general, any positive shift of the marginal cost function for black electricity (such as may result from an increase of input prices in the generation of black electricity) will induce a reduction in the generation of green electricity.

and the wholesale price is reduced. The extra remuneration for green electricity generation in the TGC system is composed of the margin between the wholesale price and the end-user price. As the wholesale price increases in response to the harsher emission constraints, this margin, equal to the TGC price multiplied by the percentage requirement, will be reduced. To recognize this, assume, as an example, that this margin is reduced by one cent and that the percentage requirement is 20%. In such a case, the TGC price will be reduced by $1/0.2 = 5$ cents. Therefore, the total remuneration to producers of green electricity (i.e., the sum of the wholesale price and the TGC price) is reduced. Consequently, the equilibrium effects of harsher CO₂ emission constraints are reductions in both black and green electricity generation.

3. Trade in electricity

In this section, we investigate how a TGC system functions in an open economy. Thus, we expand 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. In addition, we introduce the "trade variables", m and n , representing imports of electricity and TGCs, respectively. In the exposition to follow, we apply the subscript i , where $i = A, B$. Demand may differ between the two countries, and it is assumed that the inverse demand functions are given by:

$$p_i(x_i), \text{ where } \frac{\partial p_i(x_i)}{\partial x_i} < 0.$$

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 in each of the countries.

The cost function of black electricity in country i is given by:¹⁵

¹⁵ The cross-effects may differ between the countries because the share of black electricity in each country may be different. If the price of emission permits increases, the country with the highest share of black electricity will experience the largest shift of its marginal cost curve.

$$c_i = c_i(y_i, \beta), \text{ where } \frac{\partial c_i}{\partial y_i} > 0, \frac{\partial^2 c_i}{\partial y_i^2} \geq 0, \text{ and } \frac{\partial^2 c_i}{\partial y_i \partial \beta} > 0.$$

The cost function of green electricity in country i is given by:

$$h_i = h_i(z_i), \text{ where } \frac{\partial h_i}{\partial z_i} > 0 \text{ and } \frac{\partial^2 h_i}{\partial z_i^2} > 0.$$

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. 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 $m_A^* = -m_B^*$.

It is easily recognized that the optimization problems and the first-order conditions for the agents in each of the countries must be similar to those under autarky, except that imports and exports must be accounted for explicitly. Therefore, the equilibrium conditions for each of the markets in each of the countries can be expressed as follows:

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

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

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

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

Inserting 8) and 9) into 6), we find that the equilibrium end-user price can be written as a linear combination of the marginal costs of black and green electricity:

$$10) \quad p_i(x_i^*) = (1 - \alpha_i) \frac{\partial c_i(y_i^*, \beta)}{\partial y_i} + \alpha_i \frac{\partial h_i(z_i^*)}{\partial z_i}.$$

3.2. The effects of the percentage requirement as a means for promoting green electricity generation

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. More precisely, we seek to determine the effects of an increase in country A's percentage requirement on green and black electricity generation and electricity consumption in both countries.

Taking the implicit derivate of expression 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 $Y = y_A + y_B$, $D_i = \frac{\partial p_i}{\partial x_i} - (1 - \alpha_i)^2 \frac{\partial^2 c_i}{\partial y_i^2} - \alpha_i^2 \frac{\partial^2 h_i}{\partial z_i^2} < 0$ for $i = A, B$ and

$$E_i = \left[\alpha_i^2 \frac{\partial^2 h_i}{\partial z_i^2} - \frac{\partial p_i}{\partial x_i} \right] \frac{\partial^2 c_i}{\partial y_i^2}.$$

An inspection of the signs shows that the numerator is positive, whereas the denominator is negative. Therefore, the effect on the combined generation of black electricity in the two countries is negative.

Furthermore, it can be shown that:¹⁶

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

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

$$\frac{dx_B}{d\alpha_A} > 0 \text{ and } \frac{dz_B}{d\alpha_A} > 0. \text{ In other words, somewhat surprisingly, the increase of the percentage}$$

requirement in country A leads to an increase in both electricity consumption and green electricity generation in country B. The other effects are indeterminate.¹⁷

From this analysis, we note in particular that the effect of an increase in country A's percentage requirement on green electricity generation in that country is indeterminate. However, the effect on country B is determinate. The generation of green electricity in country B will *increase*. Furthermore, electricity consumption in country B will increase, whereas the generation of black electricity will fall in both countries. As explained earlier, 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 influence the demand for electricity in country B. The reduced wholesale price implies that electricity becomes cheaper in country B, leading to an increase in electricity consumption in this country. 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 between the countries, 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.

¹⁶ Proofs may be obtained from the authors upon request.

¹⁷ 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.

3.3. The effects of harsher CO₂ emission constraints

Harsher CO₂ emission constraints imply a reduction of green electricity generation in both countries. To see this, we rearrange 10) to obtain:

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

Differentiating this expression, we arrive at:

$$11) \frac{\partial p_i}{\partial x_i} \frac{dx_i}{d\beta} - \alpha_i \frac{\partial^2 h_i}{\partial z_i^2} \frac{dz_i}{d\beta} = (1 - \alpha_i) \frac{dq_M}{d\beta}, \quad i = A, B.$$

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

$$12) \frac{1}{1 - \alpha_A} \left(\frac{\partial p_A}{\partial x_A} \frac{1}{\alpha_A} - \alpha_A \frac{\partial^2 h_A}{\partial z_A^2} \right) \frac{dz_A}{d\beta} = \frac{dq_M}{d\beta} = \frac{1}{1 - \alpha_B} \left(\frac{\partial p_B}{\partial x_B} \frac{1}{\alpha_B} - \alpha_B \frac{\partial^2 h_B}{\partial z_B^2} \right) \frac{dz_B}{d\beta}.$$

To obtain a contradiction, assume $\frac{dz_A}{d\beta} \geq 0$. Inspecting the signs of expression 12), we see that

this implies that $\frac{dz_B}{d\beta} \geq 0$, $\frac{dx_A}{d\beta} \geq 0$, $\frac{dx_B}{d\beta} \geq 0$, and $\frac{dq_M}{d\beta} \leq 0$. From 9), we see that $\frac{dq_M}{d\beta} \leq 0$

implies that $\frac{dy_A}{d\beta} < 0$ and $\frac{dy_B}{d\beta} < 0$. Upon applying 7) and eliminating m_i , we find that:

$$13) (1 - \alpha_A) \frac{dx_A}{d\beta} + (1 - \alpha_B) \frac{dx_B}{d\beta} = \frac{dy_A}{d\beta} + \frac{dy_B}{d\beta}.$$

An inspection of the signs of expression 13) 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 expression 13), it is apparent that the total generation of black electricity must be reduced, whereas expression 12) makes it clear that the wholesale price of electricity will have to go up. The intuition behind the reduction of green electricity as a result

of harsher emission constraints is the same as the intuition for the autarky case, discussed in section 2.2.

4. Trade in electricity and TGCs

The focus of this section is on the case where both electricity and TGCs can be traded between two countries. This implies that both the wholesale price of electricity and the price of TGCs are common between the countries. 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 certificates implies that the relative share of green electricity generated in one country may be different from the percentage requirement (see expression 15). The equilibrium can be expressed as follows:

$$14) \quad p_i(x_i^*) = q_M^* + \alpha_i s_M^* ;$$

$$15) \quad x_i^* = y_i^* + z_i^* + m_i^* = \frac{z_i^* + n_i^*}{\alpha_i} ;$$

$$16) \quad q_M^* + s_M^* = \frac{\partial h_i(z_i^*)}{\partial z_i} ;$$

$$17) \quad q_M^* = \frac{\partial c_i(y_i^*, \beta)}{\partial y_i} .$$

Inserting 14) and 15) into 12), we find again that the equilibrium end-user price may be written as a linear combination of the marginal costs of black and green electricity:

$$18) \quad p_i(x_i^*) = (1 - \alpha_i) \frac{\partial c_i(y_i^*, \beta)}{\partial y_i} + \alpha_i \frac{\partial h_i(z_i^*)}{\partial z_i} .$$

4.2. The effects of the percentage requirement as a means for promoting green electricity generation

Once again, we focus on the effect of changing the percentage requirement. The analysis shows that it is possible to determine only the effect on black electricity generation in this case. Again, an increase in the percentage requirements leads to a reduction of green electricity generation; i.e., we have $\frac{dY}{d\alpha_A} < 0$. To realize this, assume the opposite result,

namely, that an increase of α_A , the percentage requirement in country A, either increases, or has no effect on, the total generation of black electricity. 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 also increase. From equation 14), we notice that 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

$$\frac{dY}{d\alpha_A} < 0.$$

As in the case of trade in electricity only, it can be shown that $\text{sign} \frac{dy_A}{d\alpha_A} = \text{sign} \frac{dy_B}{d\alpha_A}$. This

implies that the generation of black electricity is reduced in both countries; i.e., we have

$$\frac{dy_A}{d\alpha_A} < 0 \text{ and } \frac{dy_B}{d\alpha_A} < 0.$$

Considering the total generation of green electricity, the effect of increasing the percentage requirement in country A will be indeterminate again. As we now have a common market for TGCs in countries A and B, it can be shown that:

$$\text{sign} \frac{dz_A}{d\alpha_A} = \text{sign} \frac{dz_B}{d\alpha_A}.$$

Thus, in contrast to the case of trade in electricity only, an additional opportunity for trading certificates 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.¹⁸ The effect on the other variables is indeterminate. Finally, the results show that the effect on electricity consumption is indeterminate in both countries.

4.3. The effects of harsher CO₂ emission constraints

In this case, harsher CO₂ emission constraints imply a reduction of green electricity generation in both countries. To see this, first observe from expression 15) that:

$$19) \alpha_A \frac{dx_A}{d\beta} + \alpha_B \frac{dx_B}{d\beta} = \frac{dz_A}{d\beta} + \frac{dz_B}{d\beta} \text{ and}$$

$$20) (1 - \alpha_A) \frac{dx_A}{d\beta} + (1 - \alpha_B) \frac{dx_B}{d\beta} = \frac{dy_A}{d\beta} + \frac{dy_B}{d\beta}.$$

To obtain a contradiction, assume that the generation of green electricity in country A is not reduced; i.e., $\frac{dz_A}{d\beta} \geq 0$. From expression 16), we find 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 expression 19), we observe that this means that the consumption of electricity in at least *one* of the countries must be either increase or remain constant. Assume that country A does not reduce its consumption of electricity; i.e., $\frac{dx_A}{d\beta} \geq 0$ (a parallel proof exists for the case where country B does not reduce its consumption of electricity). Differentiating expression 18) in the same way that we found expression 12), we find:

$$21) \frac{1}{1 - \alpha_A} \left(\frac{\partial p_A}{\partial x_A} \frac{dx_A}{d\beta} - \alpha_A \frac{\partial^2 h_A}{\partial z_A^2} \frac{dz_A}{d\beta} \right) = \frac{dq_M}{d\beta} = \frac{1}{1 - \alpha_B} \left(\frac{\partial p_B}{\partial x_B} \frac{dx_B}{d\beta} - \alpha_B \frac{\partial^2 h_B}{\partial z_B^2} \frac{dz_B}{d\beta} \right).$$

¹⁸ Proofs may be obtained from the authors upon request.

As $\frac{dz_A}{d\beta} \geq 0$ and $\frac{dx_A}{d\beta} \geq 0$, we observe from expression 21) that $\frac{dq_M}{d\beta} \leq 0$, which implies $\frac{dy_A}{d\beta} < 0$ and $\frac{dy_B}{d\beta} < 0$. Therefore, the right-hand side of expression 20) is negative, whereas the right-hand side of expression 19) is nonnegative. For this to happen, we must have $\frac{dx_B}{d\beta} < 0$ and in addition $\alpha_A > \alpha_B$. As we have assumed that green electricity generation does not decline and we have that $\frac{dq_M}{d\beta} \leq 0$, we must have $\frac{ds_M}{d\beta} \geq 0$. From expression 12), we see that for green electricity generation to decrease in country A, we must have $\alpha_A < \alpha_B$. This contradicts the above result of $\alpha_A > \alpha_B$.

Once again, the conclusion is that green electricity generation will be reduced in both countries as a consequence of harsher emission constraints. The mechanisms underlying the result in this case, where trade takes place in electricity and TGCs, are the same as for the cases of autarky and trade in electricity only. Moreover, both total black electricity generation and total consumption of electricity will be reduced. The wholesale price of electricity will increase.

5. Discussion

One of the main conclusions of this paper is that the percentage requirement is not a very precise policy measure for stimulating investments in green electricity generation capacity. Thus, in general it is not true that an increase in the percentage requirement leads to more investments in such capacity. This result applies not only to a domestic TGC market under autarky, but also to the case where two countries trade in TGCs and electricity. 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 in demand. However, the immediate effect of a higher percentage requirement on green electricity generation cannot be guaranteed. This weakness is unique to this system. For instance, a fixed per unit subsidy system would not involve such ambiguity because an increase of a fixed per unit subsidy

definitely leads to more green generation capacity.¹⁹ Hence, if the objective is to achieve a given target of new green generation capacity, a TGC system is not 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. However, the TGC system provides a strong role for market forces and takes account of consumers' willingness to pay for electricity via the effects on demand and the end-user price. In addition, the TGC system allows for voluntary purchases of TGCs by consumers who wish to support green electricity generation.²⁰

Until recently, only a few economies had experienced running TGC markets. In the UK, TGCs were traded at around 45 GBP/MWh in 2004 (Platts, 2004). This system seems to have generated interest among investors in the construction of new green electricity generation capacity (see e.g., Butler and Neuhoff, 2004). In Sweden, trade statistics show that the TGC price has been established at a rather high level, partly because of Sweden's high percentage requirement, which was set at 9.5% in 2005, and its ambitious plans to increase the percentage requirement to 15.3% by 2010. In addition, the TGC price has been set close to the penalty price, the upper price bound. Partly for this reason, many retailers have chosen not to purchase TGCs, but instead to pay the penalty price directly, thereby avoiding some transaction costs. Indeed, in 2003, one out of four companies chose to pay the penalty rather than to purchase or use their TGCs. From 2005 onwards, a new system for determining the penalty is being introduced. Essentially, it involves setting the penalty price at 150% of the annual average of the TGC price. It is likely that the expectation of even higher TGC prices under this new system has led many companies to hoard their TGCs for future sale/use. In 2003, only 77% of issued TGCs were used. Records of the Swedish experience of TGCs are scarce and uncertainty remains as to the significance of the TGC market for generating new green electricity generation capacity.

An important result of the paper is that making CO₂ emission constraints harsher and increasing emission permit prices leads to less capacity for green electricity generation when CO₂ trade is combined with a TGC system, as explained in section 2.3. Thus, the tradable

¹⁹ 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.

²⁰ 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.

emissions permit system (TEP) and the TGC system may be viewed as alternatives. In addition, this raises the question of why two policy measures are required to achieve one goal, as in the case of the European ETS and TGC systems, which both seem to aim at achieving clean energy generation. Presumably, the answer is that the aims of the two systems are somewhat different. The TEP system is targeted at reducing the global emissions of CO₂, whereas the TGC system is targeted at achieving an electricity supply from renewable sources. Clearly, the TGC system may achieve a reduction of CO₂ 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.

A further issue is how to combine the systems in an optimal way. One option for Europe is to retain its widespread ETS system as a base and put the TGC system "on top" of this.²¹ As yet, the impact of the ETS system on the generation of green electricity is unknown. On its own, the ETS system—if it behaves according to principles—will lead to an equalization of the end-user price of electricity with the marginal cost of black electricity generation and with the marginal cost of green electricity generation plus the imputed subsidy from the ETS system. If the green electricity generation stimulated by the ETS system is not sufficient, the TGC system may act as further stimulation of green electricity generation. In that case, the equalization of the various marginal costs, including the subsidies, will be distorted, as explained in the previous sections (i.e., it will result in linear combinations of marginal costs). However, as explained earlier, more direct ways of stimulating green electricity generation include allowing per unit subsidies of green electricity generation capacity, or using an auction or a tendering system.

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 electricity generation may occur, owing to natural annual variations of wind or precipitation, which may amount to as much as $\pm 20\%$ for each for the Nordic countries. Therefore, there will be similar variations in the numbers of TGCs for sale. This in turn will give rise to a high price volatility of TGCs, involving serious price spikes. The reason for the high volatility is that TGC demand is highly inelastic because, under the percentage rule, it is only a fraction of the

²¹ On this problem, see Hindsberger et al. (2003) and Jensen and Skytte (2003).

demand elasticity for electricity. 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, the problem of price volatility may be resolved by the introduction of banking; i.e., allowing agents to keep TGCs for future use/sale. This kind of arrangement is known to have a price-dampening effect, even though occasional price spikes may still occur. In addition, banking is known to improve the functioning of the market in terms of an increased social surplus.

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. For instance, if the percentage requirement is 10%, the action of not selling a TGC will reduce consumption by 10 MWh, with a corresponding increase in the end-user price. Hence, by withholding TGCs, a producer of green electricity may significantly increase the end-user price, even though the producer's own power generation is not that large. Amundsen and Nese (2002) have shown that a TGC market with market power may even collapse into an ordinary subsidy system where the price limits (i.e., the upper-end penalty price or the lower-end resale price) constitute the per unit subsidy.

6. Summary and concluding remarks

The focus of this paper has been on the role of policy measures in TGC markets, the integration of country-specific TGC markets, and compatibility issues between TGC markets and an integrated TEP system. The analysis was based on a static long-run analytical model, which was used to deduce results for three different scenarios: first, a TGC system in an autarky; then, a TGC system implemented in a country that trades electricity with another country; and finally a case where TGC systems are implemented in two countries that trade both electricity and TGCs. For all scenarios, the effects of harsher CO₂ emissions constraints were investigated.

Our main results can be summarized as follows:

- The effect of changing the percentage requirement on the generation of green electricity is indeterminate. Thus, an increase of the percentage requirement will not necessarily lead to an increase of green electricity generation in the long run. 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.

- The effect of an increase in the percentage requirement on black electricity generation will always be negative.
- Under autarky, an increase of the percentage requirement will have an indeterminate effect on the total consumption of electricity. 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, the other country will experience an increase in both the total electricity consumption and green electricity generation. However, allowing the 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.
- In the case of TGCs working in combination with a system of traded CO₂ emission permits, a harsher CO₂ emission constraint will push the price of TGCs downwards, lowering the profits of the green electricity producers. Therefore, such a policy will induce a reduction in the generation of green electricity. This result was shown to be valid in all our specified cases.

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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