Working Paper No. 75/02

Green Certificates in an International Market

by

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SNF Project No. 3156
Effektivitet i deregulerte kraftmarkeder

The project is financed by Nordic Energy Research

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
Bergen, December 2002
ISSN 1503-2140

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January 15, 2003

Abstract

An analytical equilibrium model for a simultaneously functioning electricity market and a market for Green Certificates is formulated. The main focus is on the effects of changing the percentage requirement, which is perceived as the policy instrument affecting the level of green electricity in end use consumption. We start by looking briefly at an autarky market before opening for trade of electricity and certificates. The results show that the percentage requirement is a very imprecise instrument as to increase the provision of green electricity. In none of the cases considered will an increase of the percentage requirement in a country necessarily result in an increase in the generation of green electricity in the country itself. When opening for trade, the results show that the increase of the percentage requirement in one country can have a negative effect on green electricity generation in this country, but a positive effect in the other country. Further it is shown that in the case of an open certificate market where the certificates can be traded at a given international price, a country will maximize it's generation of green electricity by setting the percentage requirement equal to zero.

1 Introduction

The introduction of Green Certificates (GCs) as a means for increasing the generation of electricity bases on renewable sources (green electricity) is currently considered in many countries (Sweden, Denmark, UK, Holland, Italy, Belgium, Australia, USA etc.). GC systems are supposed to be introduced in Sweden and Denmark in 2003.

In short, the GC market consists of sellers and buyers of certificates. The sellers are the producers of electricity using renewable sources. The producers

*The work has been financed by the Nordic Energy Research, for which I am grateful. The author also wants to thank Eirik S. Amundsen (University of Bergen) for valuable comments. The usual disclaimer applies.

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are each allowed to sell an amount of certificates corresponding to the electricity they feed into the electricity network. The purchasers of certificates are consumers/distribution companies that are required by the government to hold a certain percentage of certificates, from here referred to as the percentage requirement, corresponding to their total consumption/end-use deliveries of electricity.[1] The GCs are seen as permits for consuming electricity. Hence, this system implies that the producers using renewable energy sources receive both the wholesale price and a certificate for each kWh fed into the electricity network. In this way the GC system is supposed to induce new investments in green electricity generation. An additional indirect effect of increasing the provision of green electricity will be to reduce CO_2 emission if the development of renewable electricity generation technologies is substituting electricity generation from fossil fuel fired plants.[2]

So far, the systems under consideration are mainly thought of as domestic systems, but the hope and aim is that an international market for GCs will be realized in the near future. International cooperation, e.g. RECS (Renewable Energy Certificate System) has been established to look into the possibilities of establishing an international market for GCs. However, the development of the national systems have happened relatively fast and it seems like the effects of a GC system have not yet been fully understood. The economic literature in this area is still scarce, but some of the contributions show that there are potential problems connected to the GC system and that the design of these systems therefore should be made carefully. Research contributions have been made by e.g. Voogt et al. (1999), Morthorst (2000 and 2001) Amundsen and Mortensen (2001 and 2002), Amundsen and Nese (2002), Bye et al. (2002) and Jensen and Skytte (2002). In this paper we will mainly build on the analyses made by Amundsen and Mortensen and Amundsen and Nese.

Amundsen and Mortensen (2001) looks at the basic features of the proposed Danish GC system. They identify a number of potential problems connected to perverse and inconclusive effects on the generation of green electricity from changes in different exogenous variables like the percentage requirement and the CO_2 emission constraint. In their model, the authors derive results for both an autarky situation and a setting which includes trade of electricity at a given international wholesale price.

Amundsen and Nese (2002) focus on the effect of market power in a GC system. Their findings suggest that faced with market power, the GC system basically collapses into a system of per unit subsidies.

In addition, concerns about lack of liquidity and large price volatility in the GC market has been expressed by critics of the GC system.

Some of the problems referred to here are to some extent believed to be related to the size of the GC market. Small markets should be more exposed to liquidity problems, price volatility and market power than larger markets.

[1] Italy is an exception in this respect as the Italian system is supposed to put the purchase obligation on the producers.

[2] Electricity based on non-renewable resources will throughout the article be referred to as black electricity.

One way to increase the size of the GC market is to open for international trade of GCs. In addition, an international market should help induce a more cost efficient development of renewable energy.

A GC-system typically consists of two policy variables, the percentage requirement and the GC-price bounds. The focus of this paper will mainly be on the percentage requirement. In the proposed GC-systems, the percentage requirement is perceived as a policy instrument affecting the level of green electricity in end use consumption. Unlike price-fixation (that leaves quantity an endogenous variable) or quantity fixation (that leaves price an endogenous variable) the percentage requirement neither fixes price nor quantity and thus leaves both variables to be endogenously determined. However, some of the articles mentioned above have shown that it is not in general true that an increase of the percentage requirement leads to an increased generation of green electricity in equilibrium. The analyses have, however, so far been done on an autarky market and on a market with trade of electricity at a given international wholesale price. In this paper, we will develop the analysis further by allowing also for trade of GCs. We will do the analysis step by step, starting by referring the results for an autarky market. Thereafter we will open for trade of electricity, trade of GCs, and trade of both electricity and GCs. We will start the analysis of trade by looking at the market from the perspective of a small country, which has no effect on the international prices of electricity and GCs. Finally, we will increase the complexity by analyzing trade within the framework of a two-country model in which the prices of the traded goods are no longer given. This gives us the possibility to look into the interactions between the two countries as the prices in one of the countries can be affected by changes in demand and supply in the other country. In each of these cases, the focus will be on the effect on the key variables, i.e. generation of black and green electricity, and on consumption, from an increase of the percentage requirement.

Many of the GC-systems discussed in different countries include price bounds for the GC-price. The introduction of a lower price bound is used in order to provide the producers of green electricity with a guaranteed minimum price for their certificates. This means that the producers can produce as many GCs they want and the State will guarantee that they get paid the minimum price bound. The upper price bound is meant to provide the consumers with a guarantee that they will not have to pay an "unreasonable" high price for their necessary certificates. At a binding upper price bound the consumers are offered the possibility to pay a fine equal to the upper price bound to the State instead of buying GCs. A GC system in which the GC-price is at one of the price bounds is nothing else than a system of per unit subsidies. In this paper we are using a long run model, and it does not seem relevant to consider a GC system in which the GC-price stays at one of the price bounds in the long run. If this is the case, it should just be replaced by a traditional subsidy scheme. Thus, we will in the major part of our analysis assume that the GC system is actually working in the sense that we get a market based price of GCs. However, we may have a situation where the price bounds are binding for shorter periods. Therefore, and also for the sake of completeness, we will also briefly discuss the importance of the price bounds with respect to our analysis.

We will build on the models developed in the above mentioned articles by Amundsen and Mortensen, and Amundsen and Nese, to investigate the effect of introducing trade. The model is an analytic equilibrium model for simultaneous functioning electricity and GC markets. In the analysis we will assume that opening the markets will remove potential market power problems. The analysis therefore assumes perfect competition in both the generation technologies (green and black), like in Amundsen and Mortensen.

The purpose of this paper is to focus on the effects of changing the policy parameters under different assumptions about the markets involved in the GC-system. As the GC-system first of all is meant to promote the generation of green electricity, the major focus will be on how changes in the policy variables affect this generation. Existing literature have already shown that these effects are not straight forward in the cases of autarky and trade of electricity at a given international price. We will investigate if and how these results change as we also open the market for GCs, not only in the case of a small country trading at given international prices, but also in the case where the trade is affecting the prices of electricity and GCs, and the end user prices, within a two-country model. It turns out that the effect on the generation of green electricity from changing the percentage requirement in most of the cases will still be indeterminate. A major result of this paper is that in none of the cases considered will an increase of the percentage requirement in a country necessarily result in an increase in the generation of green electricity in the country itself. Actually, if only GCs can be traded internationally, and if the international GC-price is given, a country will maximize it's generation of green electricity by setting the percentage requirement equal to zero. Among the other surprising and perverse results is that in the case of trade of electricity in the two-country model, an increase of the percentage requirement in one country will have an indeteterminate effect on the generation of green electricity in the country itself, while it will always induce a an increased generation of green electricity in the other country. Thus, it turns out that even if opening the markets may have a positive effect as to reduce the possibility of market power, the percentage requirement will still be a very imprecise instrument as to affect the level of green electricity in end use consumption.

The first section of the paper presents the model. The next section presents and analyses briefly the equilibrium in the case of an autarky market. Section 3 introduces three trade regimes; trade of electricity, trade of GCs, and trade of both electricity and GCs. In this section, it is assumed that the goods are traded at given international prices. In section 4, we look at the same three trade regimes, but this time within the context of a two-country model, in which the trade affects the prices. Thereafter follows a brief discussion about the other policy variable of the GC system, the GC-price bounds. Finally, the last section summarizes and concludes.

2 The model

The following model is designed to capture a long run situation for the simultaneous functioning electricity market and the markets for GCs in the case of autarky and in the case of trade at given international prices. The variables we use are defined in Table 1:

Table 1: List of variables for autarky and trade at given international prices

Variable	
consumer price of electricity	p
GC-price	s
wholesale price of electricity	q
consumption of electricity	x
generation of black electricity	y
imported quantity of black electricity	m
generation of green electricity (GCs)	z
imported quantity of green electricity (GCs)	n
percentage of green electricity consumption	α
GC demand	g

We will apply the following general functions to describe the demand and supply of electricity and GCs:

The demand for electricity is specified by the following inverse demand function:

$$p(x)\,, \text{ with } \frac{\partial p(x)}{\partial x} = p^{'}(x) < 0.$$

The cost functions for the producers of black electricity are assumed given by:

$$c = c(y)\,, \text{ with } c^{'}(y) > 0 \text{ and } c^{''}(y) > 0.$$

The rationale for choosing an increasing long run marginal cost function for the producers of black electricity is that the expansion of output may drive up the price of CO_2-emission permits or CO_2-taxes to comply with national CO_2-emission constraints.

The technologies for green electricity generation is assumed to be specified by the following cost function:

$$h = h(z)\,, \text{ with } h^{'}(z) > 0 \text{ and } h^{''}(z) > 0.$$

The rationale for choosing increasing long run cost functions for the generation of green electricity is that good sites for establishing green electricity generation, e.g. wind-mill parks, may be in scarce supply by nature.

Under autarky, the two groups of generators deliver electricity to a common wholesale market in each country, from where distribution companies purchase electricity for end-use deliveries. The distribution companies are throughout the article assumed to be perfectly competitive and act as profit maximizers.

As the markets are opened for trade, excess supply of electricity or GCs can be sold at the international market, while excess demand can be covered through import of electricity and GCs. We start by looking at the autarky situation.

3 Autarky

Assuming perfect competition in both the electricity and the GC market, all the profit maximizing market participants are price takers. The producers of black electricity act as if they jointly maximize the following profit function:

$$Max\ \pi(y) = qy - c(y)\,, \text{ s.t. } y \geq 0.$$

Of course, the first order condition for an optimum in the competitive markets state that the wholesale price equals the marginal generation costs. Thus, we have:

$$q^* = c^{'}(y)\,.$$

For each unit of green electricity generated there will be issued one certificate. The producers of green electricity will always sell all their certificates and will earn the wholesale price plus the GC-price per unit of green electricity they generate. For a given wholesale price and GC-price the generators of green electricity jointly act as to maximize:

$$Max\ \pi(z) = [q+s]\,z - h(z)\,, \text{ s.t. } z \geq 0.$$

The first order condition states that the per unit price received by the producers of green electricity equals their marginal costs:

$$q^* + s^* = h^{'}(z)\,,$$

For each unit of electricity bought and sold to the end users, the distribution companies in each country will have to pay the wholesale price plus a proportion α of the certificate price in accordance with the percentage requirement. Under the assumption of perfect competition, the distribution companies jointly act as to maximize:

$$Max\ \pi(x) = px - [q + \alpha s]\,x.$$

The first order condition is:

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

In the market for GCs the demand is given by:

$$g = \alpha x.$$

3.1 Autarky equilibrium

Given the objective functions and the first order conditions we can specify the equilibrium for the markets under autarky. The key variables used in the analysis are the equilibrium price, generated quantities of black and green electricity and total consumption of electricity. Total consumption of electricity is given by $x = \frac{z^*}{\alpha}$. The quantity constraint implied by the percentage requirement is sometimes referred to as the allowable consumption level. Assuming that $c'(y^*)$ and $h'(z^*)$ are representing the aggregate marginal cost functions, we have the following result for the key variables in equilibrium under autarky:[3]

$$p(x^*) = q^* + \alpha s^* \tag{1}$$

$$x^* = y^* + z^* = \frac{z^*}{\alpha} \tag{2}$$

$$q^* + s^* = h'(z^*) \tag{3}$$

$$q^* = c'(y^*) \tag{4}$$

3.2 Analysis

The percentage requirement, α, is in the proposed GC-systems perceived as a policy instrument affecting the level of green electricity in end use consumption. However, as shown in Amundsen and Mortensen (2001), it is not true that an increase of the percentage requirement necessarily leads to an increase in the generation of green electricity. It does, however, lead to a reduction in the generation of black electricity. As the effect on green electricity is indeterminate, the effect on total electricity generation and consumption is also indeterminate, i.e. we have $\frac{dy^*}{d\alpha} < 0$ while $sign\ \frac{dz^*}{d\alpha}$ and $sign\ \frac{dx^*}{d\alpha}$ are indeterminate.[4]

4 Trade at given international prices

In this section we will introduce trade as we look at the three different trade regimes. In the analysis of trade, we will start by looking at trade of only electricity, then we assume that only GCs can be traded, and finally we analyze the case where both electricity and GCs can be traded internationally. In this

[3] The market equilibrium under autarky is as specified in Amundsen and Mortensen (2001, 2002).

[4] For a formal proof of the general case see Amundsen and Nese (2002). See also Bye et al. (2002) and Jensen and Skytte (2002) that obtain more structure on the results by applying specific functions on basically similar models as in Amundsen and Mortensen (2001, 2002), e.g. how total electricity consumption varies as a function of the percentage requirement.

section we assume that we look at a small country that has no influence on international prices.[5]

4.1 Trade of electricity

We are now assuming that electricity can be traded at an international market. It is also assumed that there are neither any transaction costs associated by this trade, nor are there any transmission limits between the markets. As we look at a small country with no influence on international prices, the wholesale price can be seen as fixed, represented by q_M. We can in this case think of a common market for electricity in the sense that the generators observe the market price and then supplies the relevant quantity to the common market. The distribution companies will then purchase the electricity at the common market, but the GCs will have to be purchased domestically. The certificates are only financial assets, so the certificates and the green electricity that has produced the certificates can be purchased separately. However, in this case where only electricity can be traded internationally, the demand for GCs must be covered through green electricity generated domestically.

We will not go through the model specification again as the only change from the autarky case is that the wholesale price of electricity, q, is now replaced by the internationally given wholesale price, q_M, in the objective functions and the first order conditions.

4.1.1 Equilibrium for the case of trade of electricity

The possibility of trade of electricity is reflected by the import variable, m^*, in equation (6). We will then have the following competitive equilibrium solution:

$$p(x^*) = q_M^* + \alpha s^* \tag{5}$$

$$x^* = y^* + z^* + m^* = \frac{z^*}{\alpha} \tag{6}$$

$$q_M^* + s^* = h'(z^*) \tag{7}$$

$$q_M^* = c'(y^*) \tag{8}$$

4.1.2 Analysis

Focusing on the effect of changing the percentage requirement, Proposition 1 shows that the effect on the generation of green electricity is again indeterminate, the generation of black electricity is unaffected, while the consumption will decrease from an increase of the percentage requirement.

[5] These cases have to some extent also been treated in Hansen (2001).

Proposition 1 *In the case of trade of electricity at a given international wholesale price, the percentage requirement, α, has the following effects:* $\frac{dy^*}{d\alpha} = 0$, $\frac{dx^*}{d\alpha} < 0$, *while sign* $\frac{dz^*}{d\alpha}$ *is indeterminate.*

Proof. *First, the given international wholesale price of electricity implies that the generation of black electricity is not affected by an increase of α, i.e. we have* $\frac{dy^*}{d\alpha} = 0$. *Then, inserting* (7) *and* (8) *into* (5) *yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.* $p(x^*) = (1-\alpha)c'(y^*) + \alpha h'(z^*)$. *Take the implicit derivatives of this expression with respect to α and arrive at:* $\frac{dz^*}{d\alpha} = \frac{\alpha s^* + x^*(\partial p/\partial x)}{D}$ *and* $\frac{dx^*}{d\alpha} = \frac{s^* + x^* \alpha h''(z^*)}{D}$, *with* $D = \frac{\partial p}{\partial x} - \alpha^2 h''(z^*) < 0$. *Inspection of signs verifies the above claims.* ■

We can explain the reduced demand by showing that the opposite, i.e. $\frac{dx^*}{d\alpha} \geq 0$, would lead to a contradiction. $\frac{dx^*}{d\alpha} \geq 0$ would necessarily imply an increased demand for green electricity, which again would lead to a higher GC-price. However, given the constant wholesale price, we see from equation (5) that this would mean that the end user price also increases. This is obviously a contradiction as an increased end user price necessarily must imply reduced electricity demand. Thus, it is obvious that we must have $\frac{dx^*}{d\alpha} < 0$. The open electricity market implies, however, that the generation of green electricity can go in both directions, even if the electricity demand is reduced. The increased percentage requirement is working as to increase the demand for GCs, while the reduced electricity demand is working in the other direction. The total effect on the demand for GCs is therefore indeterminate.

4.2 Trade of GCs

Assume now that only GCs can be traded, while the market for electricity is closed. Again we want to keep it as simple as possible as we disregard potential transactions costs associated by the trade of GCs. In this case, the physical electricity must be sold domestically while the GCs are sold at an international market at a given GC-price. Note therefore, that the green electricity that produces the GCs and the GCs are sold at different markets. The generators of green electricity therefore receive the domestic wholesale price for each unit of physical electricity they sell. In addition, they receive the GC-price from the international market. Someone will perhaps question the relevance of a system in which there is trade of GCs, but no trade of electricity. However, as the GCs are only financial assets, they can be traded between countries without any physical transmission lines connecting them. This provides possibilities for countries in different parts of the world to utilize potential advantages stemming from trade of GCs. This can be particularly relevant in this early phase in which the different countries are at very different levels with respect to actually implement such systems. It may then very well be the case that GC systems in the beginning are implemented in countries which have no possibilities to trade electricity between them.

Again, we skip the model exercise as the only change from the autarky model is the replacement of the autarky GC-price, s, with the internationally given GC-price s_M.

4.2.1 Equilibrium for the case of trade of GCs

The relative share of green electricity generated domestically can now differ from the percentage requirement due to the possibility of import or export of GCs. This is reflected by the import variable n in equation (10). The equilibrium in the case of trade of GCs is then characterized like this:

$$p(x^*) = q^* + \alpha s_M \tag{9}$$

$$x^* = y^* + z^* = \frac{z^* + n^*}{\alpha} \tag{10}$$

$$q^* + s_M = h'(z^*) \tag{11}$$

$$q^* = c'(y^*) \tag{12}$$

4.2.2 Analysis

In the previous case, a given international wholesale price meant that the generation of black electricity was unaffected by a change in the percentage requirement. In this case of trade of GCs, the fixed international GC-price will not imply the same for the supply of green electricity as the price per unit received by the producers of green electricity also involves the domestic wholesale price. Proposition 2 below shows that the generation of green electricity will always decrease from an increase of the percentage requirement in this case. Actually, all the key variables will decrease in this case as also the generation of black electricity and the end use consumption will be reduced.

Proposition 2 *In the case of trade of GCs at a given international certificate price, the percentage requirement, α, has the following effects:* $\frac{dy^*}{d\alpha} < 0$, $\frac{dz^*}{d\alpha} < 0$ *and* $\frac{dx^*}{d\alpha} < 0$.

Proof. *Inserting (11) and (12) into (9) yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.* $p(x^*) = (1-\alpha)c'(y^*) + \alpha h'(z^*)$. *Take the implicit derivative of this expression with respect to α and arrive at:* $\frac{dy^*}{d\alpha} = \frac{(1-\alpha)s_M + x^* \quad \alpha h''(z^*) - \frac{\partial p}{\partial x}}{D}$ *with* $D = \frac{\partial p}{\partial x} - (1-\alpha)c''(y^*) - \alpha^2 h''(z^*)$. *Inspection of signs verifies the above claim. Further, we know that the internationally given GC-price implies that s_M is constant. As* $\frac{dy^*}{d\alpha} < 0$ *implies a lower q_A, we see from* (11) *that the per* *unit price received by the producers of green electricity is reduced. Therefore we have* $\frac{dz^*}{d\alpha} < 0$*. Finally,* $\frac{dy^*}{d\alpha} < 0$ *and* $\frac{dz^*}{d\alpha} < 0$ *implies* $\frac{dx^*}{d\alpha} < 0$*.* ■

In contrast to the case of trade of electricity, the reduced wholesale price of electricity cannot be compensated by an increased GC-price. Therefore, we get the perverse effect that the generation of green electricity will be reduced if the government increases the percentage requirement. The increase of α will in this case of a given GC-price function as an increase of an unit tax on consumption. This means obviously that the consumption decreases. Actually, in this special case, the domestic generation of green electricity will be maximized at $\alpha = 0$. The producers of green electricity will then obviously sell all their GCs at the international market at a price equal to s_M.

4.3 Trade of electricity and GCs

We will now combine the two previous cases assuming that the markets are open for trade of both electricity and certificates. In this case both the wholesale price and the GC-price will be given by the international markets.

4.3.1 Equilibrium for the case of trade of electricity and GCs

The equilibrium solution is in this case characterized like this:

In country A:

$$p\left(x^*\right) = q_M + \alpha s_M \tag{13}$$

$$x^* = y^* + z^* + m^* = \frac{z^* + n^*}{\alpha} \tag{14}$$

$$q_M + s_M = h'\left(z^*\right) \tag{15}$$

$$q_M = c'\left(y^*\right) \tag{16}$$

4.3.2 Analysis

With a wholesale price and a GC-price that both are given at the international market, Proposition 3 shows that a change of the percentage requirement will not affect the quantities of black and green electricity supplied by the producers in the small country. The consumption will, however, be reduced.

Proposition 3 *In the case of trade of both electricity and GCs at given international prices, the percentage requirement, α, has the following effects:* $\frac{dy^*}{d\alpha} = 0$*,* $\frac{dz^*}{d\alpha} = 0$ *and* $\frac{dx^*}{d\alpha} < 0$*.*

Proof. *Fixed wholesale and GC-prices obviously means that the price per unit of black and green electricity received by the producers are unaffected by an increase of the percentage requirement. Thus, we have* $\frac{dy^*}{d\alpha} = 0$ *and* $\frac{dz^*}{d\alpha} = 0$*. To show the effect on consumption, inserting* (15) *and* (16) *into* (13) *yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.* $p(x^*) = (1-\alpha)c'(y^*) + \alpha h'(z^*)$*. Take the implicit derivatives of this expression with respect to* α *and arrive at:* $\frac{dx^*}{d\alpha} = \frac{s_M}{\frac{\partial p}{\partial x}}$*. Inspection of signs verifies the above claim.* ■

As is easily seen from equation (13), at a fixed wholesale and GC-price, the end-user price faced by the consumers will increase from an increase of α, leading to a reduction of the electricity consumption in equilibrium. As in the previous case, the increase of α functions as an increase of an unit tax on electricity consumption.

From the above analysis we can conclude that the uncertain and to some extent perverse effect of changes in the percentage requirement continue as the markets are opened for trade. At least this is the case when the international prices of the traded goods are given. We will now continue the analysis within the context of a two-country model, in which the international wholesale- and GC-prices are no longer fixed.

5 Two countries: The model

The following model is designed to capture a long run situation for the simultaneous functioning electricity market and the markets for GCs in two countries; country A and country B. The variables we use are defined in Table 1:

Table 2: List of variables for the two-country model

Variable	Country A	Country B
consumer price of electricity	p_A	p_B
GC-price	s_A	s_B
wholesale price of electricity	q_A	q_B
consumption of electricity	x_A	x_B
generation of black electricity	Y_A	Y_B
quantity of black el. sold domestically	y_{AA}	y_{BB}
exported quantity of black el.	y_{AB}	y_{BA}
generation of green electricity (GCs)	Z_A	Z_B
quantity of green el. (GCs) sold domestically	z_{AA}	z_{BB}
exported quantity of green el. (GCs)	z_{AB}	z_{BA}
percentage of green electricity consumption	α_A	α_B
GC demand	g_A	g_B

We will apply the following set of general functions to describe the demand and supply of electricity and GCs:

The demand for electricity can be different in the two countries and the inverse demand functions are assumed to be:

In country A:

$$p_A(x_A), \text{ with } \frac{\partial p_A(x_A)}{\partial x_A} = p_A^{'}(x_A) < 0,$$

and in country B:

$$p_B(x_B), \text{ with } \frac{\partial p_B(x_B)}{\partial x_B} = p_B^{'}(x_B) < 0.$$

We will assume that the technologies used to generate black and green electricity may be different in the two countries, but that the technologies are country specific. Thus, all the generators of black electricity in country A have the same cost function, as will the generators of green electricity. The technologies used by the producers in country B can be different from those used in country A and thus lead to comparative advantages/disadvantages in one or both of the technologies.

The cost functions for the producers of black electricity are assumed given by:

For the producers located in country A:

$$c_A = c_A(Y_A), \text{ with } c_A^{'}(Y_A) > 0 \text{ and } c_A^{''}(Y_A) > 0,$$

and in country B:

$$c_B = c_B(Y_B), \text{ with } c_B^{'}(Y_B) > 0 \text{ and } c_B^{''}(Y_B) > 0.$$

The technologies for green electricity generation in the two countries are assumed to be specified by the following cost functions:

For the producers in country A:

$$h_A = h_A(Z_A), \text{ with } h_A^{'}(Z_A) > 0 \text{ and } h_A^{''}(Z_A) > 0,$$

and in country B:

$$h_B = h_B(Z_B), \text{ with } h_B^{'}(Z_B) > 0 \text{ and } h_B^{''}(Z_B) > 0.$$

5.1 Trade of electricity

Again, we start the analysis assuming that only electricity can be traded between two countries. As in the previous section it is assumed that there are neither any transaction costs associated by this trade, nor are there any transmission limits between the countries. Thus, the markets for electricity in country A and B can in this case be seen as a common market with a common wholesale price, i.e. $q_A = q_B = q_M$.

In this case, the producers of black electricity act as if they jointly maximize the following profit functions:

In country A:

$$Max\ \pi\left(Y_A\right) = q_M Y_A - c_A\left(Y_A\right), \text{ s.t. } Y_A \geq 0,$$

and in country B:

$$Max\ \pi\left(Y_B\right) = q_M Y_B - c_B\left(Y_B\right), \text{ s.t. } Y_B \geq 0.$$

Under perfect competition, the first order conditions in this case must imply that in equilibrium the marginal cost of the producers of black electricity in both countries are equal to the common wholesale price of electricity. Thus, we have:

$$q_M = c_A^{'}\left(Y_A\right) = c_B^{'}\left(Y_B\right).$$

The generators of green electricity now jointly act as to maximize:
In country A:

$$Max\ \pi\left(z_A\right) = \left[q_M + s_A\right] Z_A - h_A\left(Z_A\right), \text{ s.t. } Z_A \geq 0,$$

and in country B:

$$Max\ \pi\left(z_B\right) = \left[q_M + s_B\right] Z_B - h_B\left(Z_B\right), \text{ s.t. } Z_B \geq 0.$$

The first order conditions obviously are just:
In country A:

$$q_M + s_A = h_A^{'}\left(Z_A\right),$$

and in country B:

$$q_M + s_B = h_B^{'}\left(Z_B\right).$$

The distribution companies jointly act as to maximize:
In country A:

$$Max\ \pi\left(x_A\right) = p_A x_A - \left[q_M + \alpha_A s_A\right] x_A,$$

and in country B:

$$Max\ \pi\left(x_B\right) = p_B x_B - \left[q_M + \alpha_B s_B\right] x_B.$$

This yields the following first order conditions:
In country A:

$$p_A = q_M + \alpha_A s_A,$$

and in country B

$$p_B = q_M + \alpha_B s_B.$$

The demand for GCs is as usual given by:
In country A:

$$g_A = \alpha_A x_A,$$

and in country B:

$$g_B = \alpha_B x_{B.}$$

5.1.1 Electricity trade

As we have a common market for electricity in this case, the market balance condition for electricity can be expressed as:

$$Y_A + Z_A + Y_B + Z_B \geq x_A + x_B,$$

i.e. total supply of electricity from the generators in country A and B must be at least as large as total demand for electricity in these two countries. However, when characterizing the equilibrium for the two countries it is convenient to separate the generated quantities of black electricity in each country into quantity sold to consumers in the home country and electricity sold to the consumers in the other country. For the quantity of black electricity generated in country A, Y_A, we then have $Y_A = y_{AA} + y_{AB}$, with y_{AA} being the quantity sold to domestic consumers, while y_{AB} represents the quantity exported to the consumers in country B. In the same way we have $Y_B = y_{BB} + y_{BA}$.

Export of electricity will happen when the domestic supply exceeds domestic demand. Obviously electricity will be exported only if there exist a supply deficit in the other country. In this model of only two countries, the export from one of the countries must equal the import of the other country. Thus, only one of the trade variables y_{AB} and y_{BA} can be positive in equilibrium, the other will always be zero, i.e. we have the trade of electricity specified as:

$$y^*_{AB} = \max\left(0; Y^*_A + Z^*_A - x^*_A\right),$$

and

$$y^*_{BA} = \max\left(0; Y^*_B + Z^*_B - x^*_B\right).$$

5.1.2 Equilibrium for the case of trade of electricity

Assuming that $c'_A\left(Y^*_A\right)$, $h'_A\left(Z^*_A\right)$, $c'_B\left(Y^*_B\right)$ and $h'_B\left(Z^*_B\right)$ are representing the aggregate marginal cost functions in the two countries, we have the following result for the key variables in equilibrium in the case of trade of electricity:

In country A:

$$p_A\left(x^*_A\right) = q^*_M + \alpha_A s^*_A \tag{17}$$

$$x^*_A = y^*_{AA} + Z^*_A + y^*_{BA} = \frac{Z^*_A}{\alpha_A} \tag{18}$$

$$q_M^* + s_A^* = h_A^{'}(Z_A^*) \tag{19}$$

$$q_M^* = c_A^{'}(Y_A^*) \tag{20}$$

In country B:

$$p_B(x_B^*) = q_M^* + \alpha_B s_B^* \tag{21}$$

$$x_B^* = y_{BB}^* + Z_B^* + y_{AB}^* = \frac{Z_B^*}{\alpha_B} \tag{22}$$

$$q_M^* + s_B^* = h_B^{'}(Z_B^*) \tag{23}$$

$$q_M^* = c_B^{'}(Y_B^*) \tag{24}$$

5.1.3 Analysis

We will focus the analysis on the effects of an increase of the percentage requirement in one of the countries. We do this because it gives a better understanding of the interactions between the countries. Neither will it be necessary for the countries involved in the trade to have the same percentage requirement. The analysis will then investigate the effects on the generation of black and green electricity, and on consumption, in both countries, from an increase of the percentage requirement in country A.[6]

Proposition 4 shows some interesting results. In country A, an increase of the percentage requirement will definitely lead to a reduced demand for black electricity, which means that the wholesale price of electricity falls, see equation (20). Note that we use the symbol Y, representing the total supply of black electricity to the common market from the two countries, i.e. $Y = Y_A + Y_B$. A common electricity market with a common wholesale price must imply that the effect on the generation of black electricity from an increase of α_A is the same in both countries. Thus, $\frac{dY^*}{d\alpha_A} < 0$ means that both $\frac{dY_A^*}{d\alpha_A}$ and $\frac{dY_B^*}{d\alpha_A}$ are negative. The effects on the generation of green electricity and on electricity consumption in country A are again indeterminate, as they were both under autarky and in the case of trade of electricity at a given international wholesale price. Thus, the effects with respect to country A are as in the previous cases. Within the two-country model, however, also country B will be affected by a change of the percentage requirement in country A. As already mentioned above, the generation of black electricity will be reduced also in this country

[6] It should be noted that the results would be the same if we looked at a change of the percentage requirement in country B. Of course the analysis could also be made assuming that the countries have a common percentage requirement, but this will not give any additional information. The effects of changes in a common α will be identical to the effects on the key variables in country A from a change in α_A.

as we now have a common market for electricity. However, and this is a quite surprising result, both the generation of green electricity and the consumption of electricity in country B will actually increase from the increase in α_A.[7]

Proposition 4 *In the case of trade of electricity in the two country model, the percentage requirement, α_A, has the following effects: i) $\frac{dY^*}{d\alpha_A} \lessgtr 0$, ii) sign $\frac{dz_A^*}{d\alpha_A}$ and sign $\frac{dx_A^*}{d\alpha_A}$ are indeterminate, and iii) $\frac{dz_B^*}{d\alpha_A} > 0$ and $\frac{dx_B^*}{d\alpha_A} > 0$.*

Proof. *i) Inserting (19) and (20) into (17) yields the electricity price in country A as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e. $p_A(x_A^*) = (1-\alpha_A) C'(Y^*) + \alpha_A h_A'(z_A^*)$. Take the implicit derivatives of this expression with respect to α_A and arrive at: $\frac{dY^*}{d\alpha_A} = \frac{(1-\alpha_A)+x_A^* \alpha_A h_A''(z_A^*)-\alpha_A^2 h_A''(z_A^*)}{D}$, $\frac{dz_B^*}{d\alpha_A} = -\frac{\alpha_B(1-\alpha_B)C''(Y^*)x_A^*}{\alpha_A D}$ and $\frac{dx_B^*}{d\alpha_A} = -\frac{(1-\alpha_B)C''(Y^*)x_A^*}{D}$, with $D = \frac{\partial p_A}{\partial x_A} - (1-\alpha_A)^2 C''(Y^*) - \alpha_A^2 h_A''(z_A^*) < 0$. Inspection of signs verifies the above claim.*

ii) To show that $\frac{dz_A^*}{d\alpha_A}$ and $\frac{dx_A^*}{d\alpha_A}$ are indeterminate, it suffices to give examples satisfying the assumptions of the model. Examples are provided in appendix B.

iii) Inserting (23) and (24) into (21) yields the electricity price in country B as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e. $p_B(x_B^*) = (1-\alpha_B) C'(Y^*) + \alpha_B h_B'(z_B^*)$. Take the implicit derivatives of this expression with respect to α_A and arrive at: $\frac{dz_B^*}{d\alpha_A} = -\frac{\alpha_B(1-\alpha_B)C''(Y)x_A}{\alpha_A D}$ and $\frac{dx_B^*}{d\alpha_A} = -\frac{(1-\alpha_B)C''(Y)x_A}{D}$, with $D = \frac{\partial p_A}{\partial x_A} - (1-\alpha_A)^2 C''(Y^*) - \alpha_A^2 h_A''(z_A^*) < 0$. Inspection of signs verifies the above claims. ■

In order to understand and explain this surprising result with respect to the increase of the generation of green electricity in country B, it is enough to explain why the electricity demand in country B, x_B, must increase. As there is no trade of GCs in this case, an increase of x_B must necessarily imply an increase in the generation of green electricity in country B to cover the increased demand for certificates. In order to obtain a contradiction, assume that the opposite is true, i.e. $\frac{dx_B^*}{d\alpha_A} \leq 0$. For this to be the case, the end user price of electricity in country B, p_B, must be at least as high as before the increase of α_A. As we know that q_M is reduced and α_B is unchanged, we see from equation (21) that $\frac{dp_B}{d\alpha_A} \geq 0$ must imply that s_B is increased by at least $\frac{1}{\alpha_B}$ times the decrease of q_M. As $\alpha_B < 1$, this must imply that the price per unit received by the

[7] In the proofs for the cases involving trade of electricity we will assume that $C(Y)$ represents the horizontal sum of $C(Y_A)$ and $C(Y_B)$, with $Y = Y_A + Y_B$ being the total quantity of black electricity generated in the two countries. This assumption is straight forward as we know that the common electricity market induces a common wholesale price of electricity, q_M, in the two countries, which means that we have $q_M = C'(Y_A^*) = C'(Y_B^*)$ in equilibrium. Thus we also have $C'(Y) = C'(Y_A) + C'(Y_B)$ and $C''(Y) = C''(Y_A) + C''(Y_B)$.

producers of green electricity in country B, $q_M + s_B$, has increased as compared to before the increase of α_A. This means that the generation of green electricity in this country has increased. However, this contradicts the above assumption of $\frac{dx_B^*}{d\alpha_A} \leq 0$, as a non-increase of the electricity consumption in country B is not consistent with an increase of the generation of green electricity in this country. The increase of the percentage requirement in country A must therefore imply an increase of the electricity consumption, and thus also in the generation of green electricity, in country B.

We also note that even if the generation of black electricity falls also in country B, the supply of black electricity to the consumers in country B will increase. The reduction in generated quantity is therefore due to the reduced net export of black electricity from country B to country A.

Thus, we have the paradoxical situation that while an increase of the percentage requirement in country A may actually lead to a reduction of the generation of green electricity in country A, it will always increase the generation of green electricity in country B

5.2 Trade of GCs

Assume now that only GCs can be traded, while the market for electricity is closed. In this case, the physical electricity must be sold domestically while the GCs can be sold in a common market at the common GC-price s_M.[8]

The only changes of the objective functions and the first order conditions from the previous case are the replacements of the common wholesale price, q_M, with the domestic wholesale prices, q_A and q_B, and the introduction of a common GC-price, s_M, instead of the country specific GC-price, s_A and s_B.

5.2.1 GC-trade

As the GC prices in the two countries are equal, the trade of GCs will be given by the following two expressions in equilibrium:

Export of GCs from country A:

$$z_{AB}^* = \max\left(0; Z_A^* - \alpha_A x_A^*\right),$$

and from country B:

$$z_{BA}^* = \max\left(0; Z_B^* - \alpha_B x_B^*\right).$$

In this case, there will be export of GCs if the domestic supply is larger than the domestic demand. As in the case of trade of electricity, only one of these trade variable can be positive in equilibrium in our two-country model.

[8] The introduction of GC-price bounds can have the effect as to make the GC-prices different beween the trading countries. This will be treated later in this paper.

5.2.2 Equilibrium for the case of trade of GCs

In the case of trade of GCs we will then have the following competitive equilibrium solution for the key variables:

In country A:

$$p_A\left(x_A^*\right) = q_A^* + \alpha_A s_M^* \tag{25}$$

$$x_A^* = Y_A^* + z_{AA}^* = \frac{z_{AA}^* + z_{BA}^*}{\alpha_A} \tag{26}$$

$$q_A^* + s_M^* = h'\left(Z_A^*\right) \tag{27}$$

$$q_A^* = c'\left(Y_A^*\right) \tag{28}$$

In country B:

$$p_B\left(x_B^*\right) = q_B^* + \alpha_B s_M^* \tag{29}$$

$$x_B^* = Y_B^* + z_{BB}^* = \frac{z_{BB}^* + z_{AB}^*}{\alpha_B} \tag{30}$$

$$q_B^* + s_M^* = h'\left(Z_B^*\right) \tag{31}$$

$$q_B^* = c'\left(Y_B^*\right) \tag{32}$$

5.2.3 Analysis

As is shown in Proposition 5, it turns out that increasing α_A as usually leads to a reduction in the demand for black electricity in country A. However, in contrast to the case of trade of electricity, the effect on generation of black electricity in country B is now indeterminate. Actually, in this case it is only the effect on generation of black electricity in country A that is certain. All the other key variables in both countries are indeterminate.

Proposition 5 *In the case of trade of GCs in the two country model, the percentage requirement, α_A, has the following effects: i) $\frac{dy_A^*}{d\alpha_A} < 0$, and ii) sign $\frac{dz_A^*}{d\alpha_A}$, sign $\frac{dx_A^*}{d\alpha_A}$, sign $\frac{dy_B^*}{d\alpha_A}$, sign $\frac{dz_B^*}{d\alpha_A}$ and sign $\frac{dx_B^*}{d\alpha_A}$ are all indeterminate.*

Proof. *i) Inserting (27) and (28) into (25) yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e. $p_A\left(x_A^*\right) = (1-\alpha_A)c'\left(y_A^*\right) + \alpha_A h_A'\left(z_A^*\right)$. Take the implicit derivative of this expression with respect to α_A and arrive at: $\frac{dY^*}{d\alpha_A} = \frac{(1-\alpha_A)s_M^*}{D}$, with $D = \frac{\partial p_A}{\partial x_A} - (1-\alpha_A)^2 C''\left(Y^*\right) - \alpha_A^2 h_A''\left(z_A^*\right) < 0$. Inspection of signs verifies the above claim.*

ii) *Examples satisfying the assumptions of the model are provided in appendix C.* ■

The intuition behind the indeterminate effects is that as the electricity markets are now closed, the change of the percentage requirement in country A only affects directly the common GC-price, while the wholesale price is not directly affected in country B. As the per unit price received by the producers of green electricity consists of both the wholesale price and the GC-price, the remuneration to the producers can be different in the two countries even if there is trade of GCs. The effects on the wholesale price and the end user price in country B are also uncertain. The result is then that the only certain effect is that the generation of black electricity in country A decreases.

5.3 Trade of electricity and GCs

We will now combine the two previous cases assuming that the markets are open for trade of both electricity and certificates. Both the wholesale- and GC-price will then be common between the countries, leading to a replacement of q_A and q_B with q_M, and s_A and s_B with s_M, in the objective functions and the first order conditions.

5.3.1 Equilibrium for the case of trade of electricity and GCs

As in the previous case, the relative share of green electricity generated in one country can differ from the percentage requirement due to the possibility of import or export of GCs. This is reflected in equations (30) and (34). The equilibrium will then be:

In country A:

$$p_A\left(x_A^*\right) = q_M^* + \alpha_A s_M^* \tag{33}$$

$$x_A^* = y_{AA}^* + z_{AA}^* + y_{BA}^* = \frac{z_{AA}^* + z_{BA}^*}{\alpha_A} \tag{34}$$

$$q_M^* + s_M^* = h'\left(Z_A^*\right) \tag{35}$$

$$q_M^* = c'\left(Y_A^*\right) \tag{36}$$

In country B:

$$p_B\left(x_B^*\right) = q_M^* + \alpha_B s_M^* \tag{37}$$

$$x_B^* = y_{BB}^* + z_{BB}^* + y_{AB}^* = \frac{z_{BB}^* + z_{AB}^*}{\alpha} \tag{38}$$

$$q_M^* + s_M^* = h'\left(Z_B^*\right) \tag{39}$$

$$q_M^* = c^{'}\left(Y_B^*\right) \quad (40)$$

5.3.2 Analysis

As shown in Proposition 6, we have that increasing α_A will reduce the demand for black electricity and therefore the common wholesale price decreases, leading to a drop in the generation of black electricity in both countries. The other two effects in country A, i.e. $\frac{dz_A^*}{d\alpha_A}$, $\frac{dx_A^*}{d\alpha_A}$ turns out to be indeterminate, as they have been in the two previous cases in the two-country model. In contrast to the trade of electricity case, we find that the additional opening of the GC market will mean that it is no longer certain that the increase of α_A will induce in increase of the generation of green electricity in country B. Neither can we say anything certain about the effect on end use consumption in country B.

Proposition 6 *In the case of trade of both electricity and GCs in the two-country model, the percentage requirement, α_A, has the following effects: i)* $\frac{dY_A^*}{d\alpha_A} < 0$*, while ii) sign* $\frac{dz_A^*}{d\alpha_A}$ *, sign* $\frac{dx_A^*}{d\alpha_A}$ *, sign* $\frac{dz_B^*}{d\alpha_A}$ *and sign* $\frac{dx_B^*}{d\alpha_A}$ *are all indeterminate.*

Proof. *i) Inserting (35) and (36) into (33) yields the electricity price in country A as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.* $p_A\left(x_A^*\right) = (1-\alpha_A)\,C^{'}\left(Y^*\right) + \alpha_A h_A^{'}\left(z_A^*\right)$. *Take the implicit derivative of this expression with respect to α_A and arrive at:* $\frac{dY^*}{d\alpha_A} = \frac{(1-\alpha_A)\ s_M^* + \alpha_A x_A^* h_A^{''}(z_A^*)}{D}$*, with* $D = \frac{\partial p_A}{\partial x_A} - (1-\alpha_A)^2 C^{''}\left(Y^*\right) - \alpha_A^2 h_A^{''}\left(z_A^*\right) < 0$*. Inspection of signs verifies the above claim.*

iii) Examples satisfying the assumptions of the model are provided in appendix D. ■

So far in this paper we have assumed that the GC-price is decided by the market. However, as mentioned in the introduction, many of the GC-systems discussed in different countries include price bounds for the GC-price. We will now place the focus on this other policy variable of the GC-system. The GC-price bounds will function as to restrict the variations in the GC-price. An upper price bound should be of particular significance in an early phase of a GC-system. At the time of introduction, the technologies for generation of green electricity will probably be quite immature and it may be difficult to generate enough green electricity to satisfy the percentage requirement at a reasonable cost. In such a case the upper GC-price bound will come into effect as the consumers can fulfill their percentage requirement buying GCs, or really paying a fine, to the State to be allowed to consume more electricity than α times the amount of GCs they have bought at the GC market. The lower price bound should be more relevant in a more mature GC-system to secure a minimum payment to the producers of green electricity. As argued earlier, a GC system that in the long run generates a GC-price at one of the GC-price bounds should rather be replaced by a system based on direct per unit subsidies. However, we may have a situation in which the price bounds are binding for shorter periods. Therefore, and also for the sake of completeness, we will now briefly discuss the importance of the price bounds with respect to our analysis.

6 Effects of GC-price bounds

We will discuss the effects of the price bounds from two different perspectives. First, we look at how the authorities can directly regulate the GC-price, upward or downwards, by changing the price bounds. Second, we will see if the comparative statics results may change if one of the price bounds is binding when the percentage requirement is changed. We will limit our discussion to the two-country model.[9] The following symbols are used to represent the GC-price bounds: $\underline{s}_A$ and $\underline{s}_B$ are the lower price bounds in country A and B, while $\overline{s}_A$ and $\overline{s}_B$ represent the upper bounds.

6.1 Price bounds in the case of trade of electricity

Assuming that we are in an equilibrium in which the GC-prices in both countries are within the price bounds, and that the authorities in one of the countries, say country A, think the current GC-price is "wrong". They can then use the price bounds to either increase or decrease the GC-price. An increase will happen if the lower price bound in country A is set to be higher that the current GC-price in country A, i.e. $\underline{s}_A > s_A^*$. Reducing the upper price bound below the current GC-price will, on the other hand, reduce s_A^*. As we are in the two-country model, this will affect the equilibrium in both countries, due to the common wholesale price of electricity, q_M.

An increase of s_A^* means that q_M is reduced. This is because it gets more expensive for the consumers in country A to fulfill the percentage requirement and they will therefore reduce their demand for electricity. The generation of green electricity in country A will, however, increase, as the producers of green electricity can sell as many certificates as they want to the authorities at the given minimum GC-price, which is higher than the former equilibrium GC-price. It is therefore worth noting that the positive effect on the generation of green electricity in country A is financed completely by the authorities, which illustrates the point that a GC-price at a price bound is equal to a direct subsidy. In country B, the effect on demand is positive, as they only face a lower wholesale price. The increased demand will obviously also induce higher generation of green electricity in country B.

A decrease of s_A^*, by lowering the upper price bound, will have the complete opposite effect. The demand in country A will increase, thus leading to an increase of q_M and a larger generation of black electricity. The lower GC-price, however, leads to a reduction of the generation of green electricity in country A as the consumers now can buy the necessary GCs from the authorities at the

[9] The effects of increasing the percentage requirment in the cases of a binding GC-price bound under autarky is treated in Amundsen and Nese (2002).

given maximum price. The effect in country B is obviously reduced demand and lower generation of green electricity. The increased generation of black electricity will just increase the net export of electricity from country B to country A.

6.2 Price bounds in the case involving trade of GCs

In order to illustrate the interaction between the countries in the cases involving trade of GCs, we will assume that the price bounds are different in the two countries. In these cases, the effects of an eventual binding price bounds will have to be considered carefully, as this will give rise to different GC-prices in the two countries.[10] With an open GC-market, a difference between the GC-prices will mean that all the certificates are sold in the market with the highest GC-price. For such a situation to be a possible equilibrium it must be so that the lowest GC-price must be equal to that country's upper price bound. This is because no certificates will be sold in this country, which means that the consumers must buy their GCs from the authorities. Such a situation is only consistent with a GC-price at the upper bound. In the other country, i.e. the country with the highest GC-price, the price can in principle be either at one of the price bound or between the bounds.

Increasing the GC-price in one of the countries, e.g. country A, by increasing the lower price bound, $\underline{s}_A$, above the valid GC-price will only generate a possible equilibrium if $\underline{s}_A > \overline{s}_B$. In equilibrium, we must therefore have $s_A^* = \underline{s}_A$, $s_B^* = \overline{s}_B$ and $\underline{s}_A > \overline{s}_B$. This will induce higher GC-prices in both countries. The effects are reduced demand and generation of black electricity, but increased generation of green electricity in both countries. Again, as in the case of trade of electricity, this increase will solely be at the expense of the authorities in the country initiating the GC-price increase.

Assume then that country A wants to reduce the s_A^* by setting the upper price bound, $\overline{s}_A$, below the current equilibrium GC-price. We then get $s_A < s_B$.The generators of green electricity will then want to sell all their GCs in country B. This will of course put a downward pressure on s_B. It is then possible that the GC-price in country B is reduced below the new s_A again so we get a new equilibrium price where the GC-prices are again equal, but at a lower level than before. Alternatively, we get a new equilibrium where the $s_B^* = \underline{s}_B$ (this conditions that $\overline{s}_A < \underline{s}_B$) or $\underline{s}_B < s_B^* < \overline{s}_B$. This will obviously depend on both elasticities and the level of the price bounds. The effect will be a lower GC-price in both countries, leading to increased demand, increased generation of black electricity, and reduced generation of green electricity in both countries.

[10] Of course, equal price bounds in the two coutries would mean that the GC-prices would be equal also in the case of binding price bounds. However, the effects with respect to our analysis would then just be equal in the two countries.

6.3 Comparative statics in cases of binding price bounds

We will now look at how the comparative statics results are affected if the price bounds are binding in one of the countries when the percentage requirement is increased. In general, the effect is that the GC-price in the country in which the price bound is binding will not be affected by the change of the percentage requirement. In the above discussion we argued that the existence of binding GC-price bounds are leading to different GC-prices between the countries in cases where the GC market is open. For these to be possible equilibria, strict, and to some extent quite unrealistic, conditions had to be fulfilled. We will therefore limit our discussion in this part to the case of trade of electricity.

6.3.1 Trade of electricity

In the case where the price bounds were not binding we had the following result (see Proposition 4): $\frac{dY^*}{d\alpha_A} < 0$, $sign\ \frac{dz_A^*}{d\alpha_A}$ and $sign\ \frac{dx_A^*}{d\alpha_A}$ were indeterminate, while $\frac{dz_B^*}{d\alpha_A}$ and $\frac{dx_B^*}{d\alpha_A}$ were both positive.

As an illustration, assume that s_A^* is at one of it's price bounds and that it remains there also after the marginal increase of α_A. First of all, the wholesale price, q_M, will still fall as it did before. The direct effect of the binding price bound is that s_A^* is unaffected by the increase of α_A. This means that the generation of green electricity will definitely be reduced as the reduction in the wholesale price, q_M, is not compensated at all by an increasing GC-price. The effect on electricity consumption is still indeterminate in country A in this case. An unchanged s_A^* and a reduced q_M has a positive effect on demand, while the increase of α_A has a negative effect. In country B, however, the effects are going in the same direction as they were in Proposition 4. In this case of a binding price bound in country A we thus have $\frac{dz_A^*}{d\alpha_A} > 0$. Otherwise, the results are as in Proposition 4.

Assume then that s_B^* is at one of it's price bounds. The reduction of q_M will, as s_B^* is fixed, mean that the generation of green electricity in country B in this case will be reduced. However, the end user price is also reduced so the electricity consumption increases in country B. The increased demand will be covered by a reduced net export of electricity from country B to country A. The effects in country A are the same as in Proposition 4. Thus, we have $\frac{dz_B^*}{d\alpha_A} < 0$, but otherwise the same results as in Proposition 4.

7 Summary and concluding remarks

In this article we have mainly focused on the percentage requirement, which is the variable that is supposed to function as the policy instrument affecting the level of green electricity in end use consumption in a Green Certificate system. We have investigated the effect of changing the percentage requirement in different market settings from autarky via trade at given international prices and finally looking at trade between two countries where the international prices are affected by the trade. When looking at trade, we have done this step by step in the sense that we started with trade of only electricity before moving to trade of only certificates, and finally opening the markets for both these goods. For each case we have derived theoretical expressions or used numerical examples to prove the effects on generation of black and green electricity and on end use consumption from an increase of the percentage requirement. Our results are summarized in the table below.

Table 3: Summary of the results

	$\frac{dy_A^*}{d\alpha_A}$	$\frac{dz_A^*}{d\alpha_A}$	$\frac{dx_A^*}{d\alpha_A}$	$\frac{dy_B^*}{d\alpha_A}$	$\frac{dz_B^*}{d\alpha_A}$	$\frac{dx_B^*}{d\alpha_A}$
Autarky	–	?	?			
Trade at given international prices						
Trade of electricity	0	?	–			
Trade of GCs	–	–	–			
Trade of electricity and GCs	0	0	–			
Trade in a two-country model						
Trade of electricity	–	?	?	–	+	+
Trade of GCs	–	?	?	?	?	?
Trade of electricity and GCs	–	?	?	–	?	?

From the above table we take particular note of the more or less paradoxical result that in neither of the cases can an increase of the percentage requirement in one of the countries guarantee an increase of the level of green electricity consumption in the country itself. This quite surprising result is followed up in the two-country analysis in which an increase of the percentage requirement in country A can, and in the case of trade of electricity always will, induce an increase of the generation of green electricity in country B. We can then have a situation where the increase of the percentage requirement in one country have a negative effect on green electricity generation in the country itself, but a positive effect in the other country.

An additional result that further increases the impression of the GC system as a system generating strange and perverse results was found in the case of trade of only GCs at a given international GC-price. It was shown that a country's generation of green electricity in this case would be maximized by setting the percentage requirement equal to zero. This would mean that the whole generation of green electricity in this country is financed from abroad.

The analysis also showed that the possibility to use the GC-price bounds as an additional policy variable in a GC system had limited effects.

Opening of the markets for electricity and GCs can to some extent reduce potential problems connected to market power, but this paper has shown that the indeterminate effect on green electricity generation from increasing the percentage requirement found under autarky continues when opening for trade.

The results from this analysis should therefore further contribute to the warnings to the countries considering to implement GC systems; a great amount of consideration should be done before implementation as the functioning of these systems seem to be far more complex than it may seem at first glance.

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Appendix

A A numerical model

In this appendix we will present a simple numerical model satisfying the assumptions we have made about the electricity market. The model will be used to provide proofs for the existence of some of the results for the two-country model referred to in Proposition 4, 5 and 6 in this article. We assume the following functions:

The inverse demand functions are given by:

For country A:

$$p_A(x_A) = a_A - b_A x_A, \text{ with } a_A,\, b_A > 0,$$

and for country B:

$$p_B(x_B) = a_B - b_B x_B, \text{ with } a_B,\, b_B > 0.$$

This gives falling demand curves as we have:

$$p_A'(x_A) = -b_A < 0$$

and

$$p_B'(x_B) = -b_B < 0$$

The technologies for generation of black electricity are summarized in the following increasing cost functions:

For country A:

$$c_A(Y_A) = k_A Y_A^2, \text{ where } k_A > 0,$$

with

$$c_A'(Y_A) = 2k_A Y_A > 0 \text{ and } c_A''(Y_A) = 2k_A \geq 0.$$

For country B:

$$c_B(Y_B) = k_B Y_B^2, \text{ where } k_B > 0,$$

with

$$c_B'(Y_B) = 2k_B Y_B > 0 \text{ and } c_B''(Y_B) = 2k_B \geq 0.$$

The producers of green electricity have the following cost functions:

For country A:

$$h_A(Z_A) = \frac{c_A}{2} Z_A^2 + g_A Z_A, \text{ where } c_A, g_A > 0,$$

with

$$h_A'(Z_A) = c_A Z_A + g_A > 0 \text{ and } h_A''(z_A) = c_A \geq 0.$$

For country B:

$$h_B(z_B) = \frac{c_B}{2} Z_B^2 + g_B Z_B, \text{ where } c_B, g_B > 0,$$

with

$$h_B^{'}(Z_B) = c_B Z_B + g_B > 0 \text{ and } h_B^{''}(z_B) = c_B \geq 0.$$

By running this model we can find the competitive equilibrium solution for the key variables in both countries for each of the three different "trade regimes".

B Proposition 5

According to Proposition 4, trade of electricity in the two-country model produces indeterminate effects with respect to the effects of a change of the percentage requirement in country A on the generation of green electricity and the electricity consumption in country A, i.e. $\frac{dz_A}{d\alpha_A}$ and $\frac{dx_A}{d\alpha_A}$ were both indeterminate.

The following parameter values are used to generate the equilibrium solution in the case where only the electricity market is open:

	a	b	c	g	k
Country A	200	0,75	30	100	3
Country B	200	0,75	30	100	2

The results showing the effect of increasing α_A from two different levels are presented in the tables below.

Country A

α_A	q_M	s_A	p_A	Y_A	z_A	x_A	y_{AB}
0.2	137.75	177.02	173.15	22.96	7.16	35.79	0
0.21	135.75	182.33	174.04	22.63	7.27	34.62	0
0.5	38	300.18	188.09	6.33	7.94	15.88	0
0.51	37	297.11	188.52	6.17	7.8	15.3	0

Country B

α_A	q_M	s_B	p_B	Y_B	z_B	x_B	Y_{BA}
0.2	137.75	177.02	173.15	34.44	7.16	35.79	5.8
0.21	135.75	183.94	172.54	33.94	7.32	36.62	4.65
0.5	38	300.18	188.09	9.5	7.94	15.88	1.56
0.51	37	302.9	188.05	9.25	7.97	15.94	1.28

Thus, the first two rows of the table above show that the generation of green electricity in country A increases from 7.16 to 7.27 when the percentage requirement in country A increases from 0.2 to 0.21. The two last rows, on the other hand, show the opposite effect as z_A there will decrease from an increase of α_A. We have thus shown that $\frac{dz_A}{d\alpha_A}$ is indeterminate.

The example above also illustrates the point that even if the generation of black electricity decreases in both countries from an increase of α_A, the consumption of black electricity will still increase in country B as its export of electricity to country A has been reduced by more than the reduction in generated quantity.

We now want to prove that the electricity consumption in country A van go in both directions if the percentage requirement in this country is increased. The above example has already that we may have $\left(\frac{dx_A}{d\alpha_A}\right) < 0$. In order to show $\left(\frac{dx_A}{d\alpha_A}\right) < 0$, we assume the following parameter values for our example:

	a	b	c	g	k
Country A	205	0.75	10	200	5
Country B	180	20	10	200	200

The result from changing α_A from 0.2 to 0.21 is presented in the tables below.

Country A

α_A	q_M	s_A	p_A	Y_A	z_A	x_A	y_{AB}
0.2	174.21	70.37	188.28	17.42	4.46	22.29	0
0.21	172.7	74.14	188.27	17.27	4.68	22.31	0

Country B

α_A	q_M	s_B	p_B	Y_B	z_B	x_B	y_{BA}
0.2	174.21	25.85	179.38	0.44	0.01	0.03	0.41
0.21	172.7	27.48	178.2	0.43	0.02	0.09	0.36

We have thus proved that $\left(\frac{dx_A}{d\alpha_A}\right)$ is indeterminate in the case of trade of electricity in the two-country model.

C Proposition 6

According to Proposition 5, $\left(\frac{dZ_A}{d\alpha_A}\right)$, $\left(\frac{dx_A}{d\alpha_A}\right)$, $\left(\frac{dy_B}{d\alpha_A}\right)$, $\left(\frac{dz_B}{d\alpha_A}\right)$ and $\left(\frac{dx_B}{d\alpha_A}\right)$ are all indeterminate in the case of trade of only GCs in the two-country model.

The following parameter values are used to generate the equilibrium solution in the case where only the GC market is open:

	a	b	c	g	k
Country A	200	0.75	50	200	3
Country B	200	0.75	30	100	3

The results from changing α_A from 0.2 to 0.21 is presented in the tables below.

Country A

α_A	s_M	q_A	p_A	y_A	Z_A	x_A	z_{AB}
0.2	214.5	137.62	180.52	22.94	3.04	25.98	0
0.21	219.0	134.85	180.84	22.47	3.08	25.55	0

Country B

α_A	s_M	q_B	p_B	y_B	Z_B	x_B	z_{BA}
0.2	214.5	134.12	177.02	22.35	8.29	30.64	2.16
0.21	219.0	133.24	177.04	22.21	8.41	30.61	2.29

The above results thus show that we may have: $\frac{dZ_A}{d\alpha_A} > 0$, $\frac{dx_A}{d\alpha_A} < 0$, $\frac{dy_B}{d\alpha_A} < 0$, $\frac{dz_B}{d\alpha_A} > 0$ and $\frac{dx_B}{d\alpha_A} < 0$.

Assume now the following parameter values:

	a	b	c	g	k
Country A	200	0.75	50	100	3
Country B	200	0.75	30	50	3

The results from changing α_A from 0.5 to 0.51 is presented in the tables below.

Country A

α_A	s_M	q_A	p_A	y_A	Z_A	x_A	z_{AB}
0.5	293.3	44.25	190.9	7.38	4.75	12.13	0
0.51	29.25	42.05	191.23	7.01	4.69	11.7	0

Country B

α_A	s_M	q_B	p_B	y_B	Z_B	x_B	z_{BA}
0.5	293.3	41.1	187.75	6.85	9.48	16.33	1.31
0.51	29.25	41.47	187.72	6.91	9.47	16.38	1.28

These results then show that we may have $\frac{dZ_A}{d\alpha_A} < 0$, $\frac{dy_B}{d\alpha_A} > 0$, $\frac{dz_B}{d\alpha_A} < 0$ and $\frac{dx_B}{d\alpha_A} > 0$.

It then remains only to show that we may have $\frac{dx_A}{d\alpha_A} > 0$. To prove this, we assume the following parameters:

	a	b	c	g	k
Country A	205	0.75	10	200	5
Country B	180	20	10	200	200

The results are as presented below:

Country A

α_A	s_M	q_A	p_A	y_A	Z_A	x_A	z_{AB}
0.2	61.2	176.67	188.91	17.67	3.79	21.45	0
0.21	64	175.44	188.88	17.54	3.94	21.49	0

Country B

α_A	s_M	q_B	p_B	y_B	Z_B	x_B	z_{BA}
0.2	61.2	146.02	158.26	0.37	0.72	1.09	0.5
0.21	64	144.0	156.8	0.36	0.8	1.16	0.57

Thus, we have shown that it is possible to have $\left(\frac{dx_A}{d\alpha_A}\right) > 0$.

The above examples have then proved that $\left(\frac{dZ_A}{d\alpha_A}\right)$, $\left(\frac{dx_A}{d\alpha_A}\right)$, $\left(\frac{dy_B}{d\alpha_A}\right)$, $\left(\frac{dz_B}{d\alpha_A}\right)$ and $\left(\frac{dx_B}{d\alpha_A}\right)$ are all indeterminate.

D Proposition 7

According to Proposition 6, $\left(\frac{dz_A}{d\alpha_A}\right)$, $\left(\frac{dx_A}{d\alpha_A}\right)$ and $\left(\frac{dz_B}{d\alpha_A}\right)$ are all indeterminate when both the electricity and the GC markets are open in the two-country model. The examples below will prove that this can be the case.

Assume first the following parameter values:

	a	b	c	g	k
Country A	200	0.75	50	200	2
Country B	200	0.75	30	100	8

The results are:

Country A

α_A	q_M	s_M	p_A	Y_A	Z_A	x_A	y_{AB}	z_{AB}
0.2	139.2	202.1	179.62	34.8	2.83	27.17	10.45	0
0.21	137.3	207.39	180.8	34.31	2.89	25.6	11.61	0
0.5	35.75	311.7	191.6	8.94	2.95	11.2	0.69	0
0.51	35	310.4	193.3	8.75	2.91	8.93	2.73	0

Country B

α_A	q_M	s_M	p_B	Y_B	Z_B	x_B	y_{BA}	z_{BA}
0.2	139.2	202.1	179.62	8.7	8.04	27.17	0	2.61
0.21	137.3	207.39	178.73	8.58	8.15	28.36	0	2.48
0.5	35.75	311.7	191.6	2.23	8.25	11.2	0	2.65
0.51	35	310.4	190.2	2.19	8.18	13.07	0	1.65

These results from the first two rows show that the following is possible: $\left(\frac{dz_A}{d\alpha_A}\right) > 0$, $\left(\frac{dx_A}{d\alpha_A}\right) < 0$ and $\left(\frac{dz_B}{d\alpha_A}\right) > 0$. From the last two rows we can see that also $\frac{dz_A}{d\alpha_A} < 0$ and $\frac{dz_B}{d\alpha_A} < 0$ are possible results.

It then remains to show that we may have $\left(\frac{dx_A}{d\alpha_A}\right) > 0$ and $\left(\frac{dx^*_B}{d\alpha_A}\right) < 0$. To prove this, we assume the following parameters:

	a	b	c	g	k
Country A	205	0.75	10	200	5
Country B	205	20	10	200	5

In addition we have assumed $\alpha_B = 0.55$.
The results are:

Country A

α_A	q_M	s_M	p_A	Y_A	Z_A	x_A	y_{AB}	z_{AB}
0.2	159.1	80.86	175.22	15.91	3.99	39.7	0	0
0.21	157.4	84.63	175.12	15.74	4.2	39.84	0	0

Country B

α_A	q_M	s_M	p_B	Y_B	Z_B	x_B	y_{BA}	z_{BA}
0.2	159.1	80.86	203.52	15.91	3.99	0.07	19.82	3.95
0.21	157.4	84.63	203.9	15.74	4.2	0.06	19.88	4.17

Thus, it is also possible to have $\left(\frac{dx_A}{d\alpha_A}\right) > 0$ and $\left(\frac{dx_B^*}{d\alpha_A}\right) < 0$.

We have then from the above examples proved that $\left(\frac{dz_A}{d\alpha_A}\right)$, $\left(\frac{dx_A}{d\alpha_A}\right)$, $\left(\frac{dz_B}{d\alpha_A}\right)$ and $\left(\frac{dx_B^*}{d\alpha_A}\right)$ are all indeterminate when both the electricity and the GC markets are open in the two-country model.