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Amundsen, Eirik S. and Nese, Gjermund

Department of Economics, University of Bergen, Norway

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EIRIK S. AMUNDSEN AND GJERMUND
NESE

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Department of Economics

UNIVERSITY OF BERGEN

Market power in interactive environmental and energy markets: The case of Green Certificates*

Eirik S. Amundsen and Gjermund Nese[†]

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[†]Eirik S. Amundsen (corresponding author): Department of Economics, the University of Bergen, Fosswinkelsgt. 6, N-5007 Bergen, Norway. Tel.: +47 55 58 92 05, Fax: +47 55 58 92 10, e-mail: eirik.amundsen@econ.uib.no. Gjermund Nese: Institute for research in economics and business administration (SNF), Breiviksveien 40, N-5045 Bergen, Norway. Phone: +47 55 95 95 21, Fax: +47 55 95 94 39, e-mail: gjemund.nese@snf.no.

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Abstract:

Markets for environmental externalities are typically closely related to the markets causing such externalities, whereupon strategic interaction may result. Along these lines, the market for Green Certificates is strongly interwoven in the electricity market as the producers of green electricity are also the suppliers of Green Certificates. In this paper, we formulate an analytic equilibrium model for simultaneously functioning electricity and Green Certificate markets, and focus on the role of market power. We consider two versions of a Nash-Cournot game: a standard Nash-Cournot game where the players treat the market for Green Certificates and the electricity market as separate markets; and a Nash-Cournot game with endogenous treatment of the interaction between the electricity and Green Certificate markets with conjectured price responses. One result is that a certificate system faced with market power may collapse into a system of per unit subsidies, as the producers involved start to game on the joint functioning of markets.

JEL classifications: C7; Q28; Q42; Q48

Key words: renewable energy, electricity, Green Certificates, market power

1 Introduction

Many developed economies have formulated policy to increase the share of energy supply obtained from renewable sources relative to that from nonrenewable sources. It is, for example, a stated European Union goal to raise the share of electricity derived from renewable sources from the current 14% to 22% of total electricity generation by 2010 (see EU/COM (2000)).¹ Similar goals exist for the United States (see, for example, EPA (2003)). Typically, the generation of green electricity has been stimulated through various kinds of subsidy schemes, including investment subsidies, tax exemptions, and per unit subsidies as implemented in, for example, Denmark, Spain and Germany. The liberalization of electricity markets has, however, induced a challenge for these economies as the policy measures chosen ought to be in accordance with market principles. One idea that has been adopted as a possible alternative to direct subsidies in many countries is to introduce markets for Green Certificates (from this point referred to as GCs). Since 1998 the Netherlands has used a system of "green labeling", which is a voluntary version of the GC-system. Denmark, Norway and Sweden² are further examples of countries introducing markets for GCs. In addition to EU Member States, economies like Australia, China, India and the US (see e.g., Giovinetto 2003) are also considering or implementing plans for GC markets.

It goes without saying that the well functioning design of GC markets is important for the proper management of the energy sector in these economies. However, despite its apparent popularity, it seems fair to say that the general functioning of GC markets are not yet fully understood. For example, some problems relating to the GC market as an instrument for inducing

¹Throughout this article, 'black electricity' refers to electricity generated from nonrenewable energy sources, while 'green electricity' refers to that obtained from renewable sources.

²The Nordic Power Exchange, Nord Pool, launched its first product related to renewable energy production in March 2004. The product is listed as Swedish "elcertificate" contracts on Nord Pool's financial market.

new capacity for green electricity production and problems related to the GC markets acting in concert with electricity markets and CO_2 markets have been investigated by Amundsen and Mortensen (2001, 2002), Jensen and Skytte (2002) and Bye (2003). The present paper investigates yet another problematic feature of the GC system. The problem emerges as electricity producers possessing market power start gaming on the joint functioning of the electricity market and the GC market. This may result in collapse of the pricing mechanism of the GC system as GC prices are always realized at either the stipulated upper or lower bound. Similar ideas on the exercise of market power through interactive markets are found in papers by Kolstad and Wolak (2003) and Chen and Hobbs (2003) concerning the joint functioning of the electricity and the NOx permit market.³

In brief, the GC market consists of sellers and buyers of certificates. The sellers are the producers of electricity using renewable sources. These producers are each issued a number of tradable certificates corresponding to the amount of electricity they feed into the network. The purchasers of certificates are consumers/distribution companies that are required by the government to hold a certain percentage of certificates ("the percentage requirement") corresponding to their total consumption/end-use deliveries of electricity.⁴ The GCs are then seen as permits for consuming electricity. Accordingly, this system implies that the producers using renewable energy sources receive both the wholesale price and a tradable certificate for each kWh fed into the electricity network. In this manner, the GC system is supposed to stimulate new investments in green electricity generation.

³In particular, Chen and Hobbs (2003) show that endogenous treatment of NOx- and electricity markets with conjectured price responses may have a substantial impact on NOx permit prices, and that the price of the permits thereby influences electricity generation.

⁴Italy is an exception in this respect as the Italian system is supposed to put the purchase obligation on the producers.

One major implication of the GC system is that the percentage requirement functions as a check on total electricity consumption, as the total number of certificates available is constrained by the total capacity of renewable technologies.⁵ For instance, a requirement of 20 % implies that total consumption can be no larger than five times the electricity produced from renewable sources, unless the price of certificates tends to increase above an upper price bound specified by the regulatory authorities. This price bound then functions as a penalty that the consumers must pay if they do not fulfill the percentage requirement. Also, the GC system may include a lower price bound, at which level the State guarantees to purchase any excess supply of certificates. The percentage requirement is thus seen as a policy parameter affecting the relative scarcity of green electricity, and in this way regulating the capacity of green electricity production. However, it is erroneous to believe that a harsher percentage requirement necessarily will result in an increased capacity of green electricity production.⁶ It may or may not. In fact, in a long-run setting it may even fall. Precise conditions for this are provided in Proposition 1.

In a competitive setting, the GC system may function as an ordinary market determining certificate prices somewhere intermediate to the upper and lower price bounds. However, and as mentioned, this may no longer be so in the face of market power. It then depends on how the producers perceive the interrelationship between the electricity market and the GC market. If the producers possessing market power in the electricity market consider the GC market as competitive (say because the GC market is part of a larger system such that GC prices may not be significantly affected by any single agent), then market power in the electricity market may

⁵In many countries, windmills constitute a significant part of the green production technology. The electricity production from windmills will typically vary significantly, giving rise to considerable variations in the total production of green electricity from year to year.

⁶In the Swedish system that became effective as of May 1 2003, the percentage requirement is set to escalate from the current 7 % to around 10 % in 2010.

still result in intermediate GC prices and a well functioning pricing mechanism. However, if the major electricity producers conjecture the impact on the GC price of their production decisions in the electricity market and start to game on this, then the GC pricing mechanism may break down. By withholding power delivered to the wholesale market, the electricity producer can exercise market power by either forcing the GC price to the upper or the lower price bound (either may be optimal for the producer) at its convenience. Basically, what is happening is that either excess demand or excess supply of GCs is created (leading to a price at the upper price bound and the lower price bound, respectively, with corresponding opposite effects on the wholesale prices). These results are identical irrespective of whether it is the producers of green or black electricity (or a duopoly of the two) that possess market power: the certificate prices will be established at either the upper or the lower bound. Thus, the GC market collapses altogether into a system of fixed GC prices instead of endogenously determined intermediate prices. In that case the GC system may equally well be replaced by a plain subsidy scheme for green power, with presumably much lower transaction costs and more precise effects on green power capacity construction.

The problem of interactive power and GC markets is then germane since the GC market in many countries is related directly to the electricity market, with identical suppliers and consumers to that of the electricity market. Thus, the effect on the GC price of changing electricity production can hardly be ignored by a major electricity producer knowing that the end user price of electricity for a large part is composed of the wholesale price and a fraction (e.g., 20%) of the GC price. Put differently, the marginal revenue of a major producer of green electricity stems from both markets (i.e., the electricity wholesale price and the certificate price), and the marginal reduction of green electricity production influences both markets (i.e., a reduction of the supply of electricity and a reduction of the supply of GCs). However, a major producer

of black electricity knows (even though she may not be directly involved in GC trade) that a marginal reduction of the electricity supply will lead to a higher end-user electricity price, hence reduced total consumption, and therefore a reduced demand for GCs. Given that market power in electricity generation is likely to exist in many economies, the possible malfunctioning of the pricing mechanism should thus be given serious consideration in the discussions and development of alternative GC systems.⁷

In the following paper, we formulate an analytic equilibrium model for a GC system and consider three main cases: perfect competition in both the electricity market and the GC market, market power in both markets using standard Cournot assumptions, and market power in both markets with endogenous treatment of the interaction between the electricity and GC markets with conjectured price responses. We also report results on various other market forms, i.e., separate market power in the generation of black electricity, separate market power in the generation of green electricity, and market power in the joint generation of green and black electricity. Throughout the paper we assume Nash-Cournot (NC-) behavior.⁸ The first section of the paper presents the model. The next sections present and analyze the equilibrium solutions for the cases listed above. The final 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 a market for GCs.⁹ We will use the following list of variables:

⁷In Denmark, for example, the production of green electricity (i.e., notably from windmills) is very concentrated: in the Jutland-Fuen price area of Nord Pool a single producer is currently active.

⁸Alternative models of describing behavior in the electricity market exist in the form of Bertrand games, supply function games and auction games, amongst others). For a discussion of why NC-behavior is a reasonable model in this regard, see Borenstein and Bushnell (1999) and Borenstein, Bushnell and Knittel (1999).

⁹For a short-run version of the model, see Amundsen and Mortensen (2001).

p = consumer price of electricity

s = price of GCs

\bar{s} = upper price bound of GCs

\underline{s} = lower price bound of GCs

q = wholesale price of electricity

x = total consumption of electricity

y = generation of black electricity

z = generation of green electricity

α = percentage requirement of green electricity consumption

g_d = demand for GCs

The inverse demand function is assumed given by:

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

The cost function for the producers of black electricity is 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 this industry 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 cost function for the producers of green electricity is assumed given by:

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

The rationale for choosing an increasing long-run marginal cost function for this industry, is that good sites for generation technologies such as wind-mills may be in scarce supply.

The two groups of producers deliver electricity to a common wholesale market, from where profit maximizing distribution companies purchase electricity for end-use deliveries.

In the model we have two markets, one market for electricity and one market for GCs. We will apply the subscripts c and m to the endogenous variables in order to indicate whether the markets are competitive, or if there is market power involved in one or both of the generation technologies. The first subscript refers to the market structure among the producers of black electricity, while the second describes the market structure for green electricity. In addition, we use the subscript M for the case where we consider market power in the joint generation of black and green electricity.

3 Perfect competition

For the case of perfect competition in both markets, the profit maximizing market participants are price takers. The producers of black electricity act as if they jointly maximize¹⁰:

$$\Pi(y) = qy - c(y).$$

The first order condition for an optimum in the competitive market is:

$$q^* = c'(y).$$

For each unit of green electricity generated one certificate will be issued. The producers of green electricity will sell all their certificates and will thus earn the wholesale price plus the GC price per unit of electricity they generate.¹¹ Jointly they act as to maximize:

$$\Pi(z) = [q + s]z - h(z).$$

The first order condition is:

$$q + s = h'(z).$$

For each unit of electricity bought and sold to the end users the distribution companies will

¹⁰To simplify the presentation we suppress subscripts whenever confusion may be avoided.

¹¹Given the assumption of perfect competition in the generation of green electricity, it is obvious that the generators will always sell all their certificates. However, and as shown later, market power in the generation of green electricity makes it relevant for these generators to consider whether they can utilize their market power to affect the price of GCs in order to increase their profit from the GC and the electricity market.

have to pay the wholesale price plus a proportion α of the certificate price in accordance with the percentage requirement. The distribution companies are throughout assumed not to enjoy any market power. Hence, jointly they act as to maximize:

$$\Pi(x) = px - [q + \alpha s]x.$$

The first order condition is:

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

In the market for GCs the demand is given by:

$$g_d = \alpha x.$$

3.1 cc-equilibrium

The consumption of electricity, and its composition of green and black electricity, in equilibrium, vary according to whether the price of GCs in equilibrium, s^* , is within the specified price interval, i.e., $\underline{s} < s^* < \bar{s}$, or on either the upper or lower price bound. If the price of GCs is within the interval, the percentage requirement is fulfilled and total consumption of electricity is given by $x = \frac{z^*}{\alpha}$ (the "allowable" consumption). If the price of GCs is at the lower bound, i.e., $s^* = \underline{s}$, the demand for GCs is less than z^* , and the excess supply of GCs is bought by the State. In this case the percentage requirement is more than fulfilled. If the price of GCs in equilibrium is equal to the upper price bound, \bar{s} , the demand for certificates exceeds the maximum possible supply. In this case, the consumers are allowed to buy more black electricity if they pay a "fine" equal to \bar{s} per unit of extra electricity consumption. Denoting the aggregate marginal cost functions by $c'(y_{cc}^*)$ and $h'(z_{cc}^*)$, the equilibrium conditions under perfect competition are¹²:

$$p(x_{cc}^*) = q_{cc}^* + \alpha s_{cc}^* \tag{1}$$

¹²In equation (2), $<$, $=$ and $>$ refer to the cases $s_{cc}^* = \underline{s}$, $\underline{s} < s_{cc}^* < \bar{s}$ and $s_{cc}^* = \bar{s}$, respectively.

$$x_{cc}^* = y_{cc}^* + z_{cc}^* \mathbf{S} \frac{z_{cc}^*}{\alpha} \quad (2)$$

$$q_{cc}^* + s_{cc}^* = h'(z_{cc}^*) \quad (3)$$

$$q_{cc}^* = c'(y_{cc}^*) \quad (4)$$

The cc-equilibrium solution is illustrated for the case of $\underline{s} < s_{cc}^* < \bar{s}$ in Figure 1. The quantity constraint implied by the percentage requirement is seen to drive a wedge equal to αs_{cc}^* between the electricity price and the marginal cost of electricity generation. The system thus involves a transfer of consumer and producer surplus from black electricity generation to a subsidy of green electricity generation.

Figure 1 here

3.2 Analysis

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 (with quantity as an endogenous variable) or quantity fixation (with price as an endogenous variable) the percentage requirement neither fixes price nor quantity, and both variables are endogenously determined. The following proposition shows that in general it is not true that an increase of the percentage requirement leads to an increased generation of green electricity in equilibrium. It does, however, lead to a reduced generation of black electricity, and therefore - from (4)- a reduced wholesale price of electricity. As the effect on green electricity is indeterminate, the effect on total consumption and end-user price is also indeterminate.¹³

¹³This is a generalization of results obtained in Amundsen and Mortensen (2001, 2002). Note that the GC system specifies the share and not the absolute amount of green electricity in end-use consumption. Hence, if the effect on end-use consumption of electricity of an increase of α is negative, the percentage requirement may be fulfilled even if the generation of green electricity is reduced. See Jensen and Skytte (2002) and Bye (2003), who obtain more structure on the results by applying specific functions on broadly similar models.

Proposition 1 *Under perfect competition in the electricity and the certificate markets, the percentage requirement, α , has the following effects: i) if $\underline{s} < s_{cc}^* < \bar{s}$, then $\frac{dy_{cc}^*}{d\alpha} < 0$ while $\text{sign}\left(\frac{dz_{cc}^*}{d\alpha}\right)$ and $\text{sign}\left(\frac{dx_{cc}^*}{d\alpha}\right)$ are indeterminate, and ii) if $s_{cc}^* = \bar{s}$ or $s_{cc}^* = \underline{s}$, then $\frac{dz_{cc}^*}{d\alpha} < 0$, $\frac{dy_{cc}^*}{d\alpha} < 0$, $\frac{dx_{cc}^*}{d\alpha} < 0$.*

Proof. *See appendix A. ■*

4 Market power in a standard Cournot setting

As argued in the introduction, there are reasons to believe that market power may exist both among the producers of black electricity and among the producers of green electricity. In the following, we approach market power from two different angles. First, we use a standard Cournot framework. In this setting the certificate price is treated as exogenous by both the producers of black and green electricity, i.e., neither of the producers realize that their quantity decisions in the electricity market affect the GC price and thereby the resulting wholesale price of electricity through the interaction between the electricity and the certificate market. In the next section we focus on the interaction between the electricity market and the GC market and make the more realistic assumption that each player may conjecture the effects on both markets of decisions made in one market. We thus include in our model an endogenous treatment of the interaction between the electricity and the GC market.

Starting with the traditional Cournot setting, we assume a duopolistic market structure, i.e., there is market power in both generation technologies such that both the producers of black and green electricity act as NC-playing oligopolists. The producers of black electricity consider then both the quantity of green electricity and the number of GCs (represented by \bar{z}) as given. The producers of green electricity consider the quantity of black electricity (represented by \bar{y}) as given. In addition, the traditional Cournot framework implies that the GC price will also be

considered as given (represented by \widehat{s}). In the NC-equilibrium none of the producers will want to change their quantity decision.

The NC-playing producers of black electricity are faced with the following residual demand function for wholesale electricity:

$$q = q(x) = p(x) - \alpha \widehat{s}, \text{ where } x = y + \bar{z},$$

and the following optimization problem:

$$\text{Max}\Pi(y, \bar{z}) = q(x)y - c(y).$$

In equilibrium the profit maximizing oligopolistic generator of black electricity will therefore equate marginal revenue with marginal cost:

$$\frac{\partial \Pi}{\partial y} = \frac{\partial q(x)}{\partial y} y + q - c'(y) = 0.$$

Or more precisely:

$$\frac{\partial \Pi}{\partial y} = \frac{\partial p}{\partial x} y + q - c'(y) = 0.$$

The producer of green electricity maximizes:

$$\Pi(z, \bar{y}) = (q + \widehat{s})z - h(z).$$

Resulting in the following first order condition:

$$\frac{\partial \Pi}{\partial z} = \frac{\partial p}{\partial x} z + q + \widehat{s} - h'(z) = 0.$$

4.1 mm-equilibrium

Using mm as the subscript for the case of market power in the traditional Cournot setting, we then have the following equilibrium solution for the key variables¹⁴:

$$p(x_{mm}^*) = q_{mm}^* + \alpha s_{mm}^* \quad (5)$$

$$x_{mm}^* = y_{mm}^* + z_{mm}^* \mathbf{S} \frac{z_{mm}^*}{\alpha} \quad (6)$$

¹⁴ Again, $<$, $=$ and $>$ in equation (14) refer to the cases $s_{mm}^* = \underline{s}$, $\underline{s} < s_{mm}^* < \bar{s}$ and $s_{mm}^* = \bar{s}$, respectively.

$$\frac{\partial p(x_{mm}^*)}{\partial x} z_{mm}^* + q_{mm}^* + s_{mm}^* = h'(z_{mm}^*) \quad (7)$$

$$\frac{\partial p(x_{mm}^*)}{\partial x} y_{mm}^* + q_{mm}^* = c'(y_{mm}^*) \quad (8)$$

4.2 Analysis

The results of the analysis are highlighted in Propositions 2 and 3.

Proposition 2 *Under duopoly with standard Cournot assumptions, the percentage requirement, α , has the following effects: i) if $\underline{s} < s_{mm}^* < \bar{s}$, then $\frac{dy_{mm}^*}{d\alpha} < 0$ (given $p''(x_{mm}^*) \leq 0$), while $\text{sign}\left(\frac{dz_{mm}^*}{d\alpha}\right)$ and $\text{sign}\left(\frac{dx_{mm}^*}{d\alpha}\right)$ are indeterminate and ii) if $s_{mm}^* = \underline{s}$ or $s_{mm}^* = \bar{s}$ and $p''(x_{mm}^*) < 0$, then $\frac{dz_{mm}^*}{d\alpha} < 0$, $\frac{dy_{mm}^*}{d\alpha} < 0$, $\frac{dx_{mm}^*}{d\alpha} < 0$.*

Proof. See appendix B. ■

These effects are thus similar to the corresponding effects under perfect competition, i.e., the effect of a percentage increase of α on black electricity is negative, while the effects on green electricity and total consumption are indeterminate.

Proposition 3 *Under duopoly with standard Cournot assumptions, we have that: i) if $\underline{s} < s_{cc}^* < \bar{s}$ and $\underline{s} < s_{mm}^* < \bar{s}$ then $z_{mm}^* < z_{cc}^*$, $y_{mm}^* < y_{cc}^*$, and $x_{mm}^* < x_{cc}^*$.*

Proof. See appendix C. ■

The effect of market power on the produced quantities are thus as expected.

5 Market power in interactive electricity and GC markets

We now take into account the interaction between the electricity and the GC markets. This framework seems to us as a more realistic representation of the functioning of the electricity market in combination with an environmental market than the traditional Cournot setting specified

in the preceding section. In particular, this appears to be the case for the GC market as this market is exclusively connected to the electricity market. The markets are thus in a sense complementary to each other. It seems unrealistic that the producers of electricity should neglect the obvious effects that their quantity decisions have on the price of GCs, and the interaction between the GC price and the wholesale price of electricity. Other environmental markets, such as, for example, markets for CO_2 emission quotas, may be linked to a number of different markets where the polluting activity occurs, e.g., electricity generation, industry production of different kinds, transportation, etc. In such cases one could perhaps argue more convincingly for the traditional Cournot setting in which the price in the environmental market is taken as given.

The optimization problems for the producers of black and green electricity in this case are identical to the corresponding problems in the preceding mm-case, except for the fact that the GC price is now a function of total quantity, i.e., we have $s = s(x)$. In their quantity decision the producers will therefore also consider the effect their decision has on the GC price, because they realize that this price affects the wholesale price of electricity ($q = p - \alpha s$).

The NC-playing producers of black electricity are faced with the following residual demand function for wholesale electricity:

$$q = q(x) = p(x) - \alpha s(x), \text{ where } x = y + \bar{z},$$

and the following optimization problem:

$$\text{Max}\Pi(y, \bar{z}) = q(x)y - c(y).$$

In equilibrium, the profit maximizing oligopolistic generator of black electricity will therefore equate marginal revenue with marginal cost:

$$\frac{\partial \Pi}{\partial y} = \frac{\partial q(x)}{\partial y} y + q - c'(y) = 0.$$

Or more precisely:

$$\frac{\partial \Pi}{\partial y} = \left[\frac{\partial p}{\partial x} - \alpha \frac{\partial s}{\partial y} \right] y + q - c'(y) = 0.$$

Correspondingly, we find the first order condition for the oligopolistic producer of green electricity to be¹⁵:

$$\frac{\partial \Pi}{\partial z} = \left[\frac{\partial p}{\partial x} + (1 - \alpha) \frac{\partial s}{\partial z} \right] z + q + s - h'(z) = 0.$$

Observe that a marginal change in the generation of electricity, both black and green, may affect the wholesale price through both the electricity market and the GC market. The effect through the electricity market stems from an ordinary effect on consumer prices, while the effect through the GC market stems from a change induced by the demand/supply of certificates (e.g., an increase in the generation of black electricity by one unit will, in equilibrium, imply an increased consumption of electricity by one unit and increased demand for certificates by α units. Correspondingly, an increase in the generation of green electricity by one unit will also increase the supply of GCs by one unit). Furthermore, observe that the demand for GCs is a derived demand equal to a given percentage of the demand for electricity. Thus, the demand for GCs is a function of the total electricity price and not the GC price. As recognized above, in (1), the electricity price is equal to the sum of the wholesale price and the GC price multiplied by the percentage requirement. It is important to note that the producers of electricity can affect the "composition" of the electricity price; for example, raise the wholesale price and lower the GC price through their production decisions.

The possibility of affecting the GC price depends, however, on whether the GC price is either at the upper and lower price bounds or between the upper and lower price bounds. If the GC price is at either of the price bounds, the effect on the GC price of a marginal change of the generation

¹⁵Following a similar line of reasoning as in the preceding case it can be shown that the producers of green electricity will never hold back certificates from the market.

of black or green electricity $\left(\frac{\partial s}{\partial y} \text{ or } \frac{\partial s}{\partial z}\right)$ is equal to zero. In these cases the wholesale price can only be affected through the electricity market (i.e., an ordinary price effect). If, however, the GC price is between the price bounds, the producers can also influence the wholesale price through the GC market. For this case, the marginal effect on the GC price $\left(\frac{\partial s}{\partial y} \text{ and } \frac{\partial s}{\partial z}\right)$ is not defined as the marginal revenue is discontinuous at this point. Accordingly, under N-C assumptions, the producers of black electricity can induce a reduction in demand for GCs and thus create an excess supply of GCs by marginally reducing the generation of black electricity. A consequence is a drop of the GC price to its lower bound and a corresponding upward jump of the wholesale price. The composition of the electricity price is thus changed to the benefit of producers of black electricity. Producers of green electricity may also use their market power to reduce their generation of green electricity marginally and thus create an excess demand for GCs. This leads to a jump of the GC price to its upper bound and a corresponding reduction of the wholesale price.

5.1 MM-equilibrium

The subscript MM is used to identify the case of market power in interactive electricity and power markets. We then have the following equilibrium solution for the key variables¹⁶:

$$p(x_{MM}^*) = q_{MM}^* + \alpha s_{MM}^* \quad (9)$$

$$x_{MM}^* = y_{MM}^* + z_{MM}^* \mathbf{S} \frac{z_{MM}^*}{\alpha} \quad (10)$$

$$\left[\frac{\partial p(x_{MM}^*)}{\partial x} + (1 - \alpha) \frac{\partial s(x_{MM}^*)}{\partial z} \right] z_{MM}^* + q_{MM}^* + s_{MM}^* = h'(z_{MM}^*) \quad (11)$$

$$\left[\frac{\partial p(x_{MM}^*)}{\partial x} - \alpha \frac{\partial s(x_{MM}^*)}{\partial y} \right] y_{MM}^* + q_{MM}^* = c'(y_{MM}^*) \quad (12)$$

¹⁶ Again, $<$, $=$ and $>$ in equation (14) refer to the cases $s_{MM}^* = \underline{s}$, $\underline{s} < s_{MM}^* < \bar{s}$ and $s_{MM}^* = \bar{s}$, respectively. For the cases of $s_{MM}^* = \underline{s}$ and $s_{MM}^* = \bar{s}$, we have $\frac{\partial s(x_{MM}^*)}{\partial z} = \frac{\partial s(x_{MM}^*)}{\partial y} = 0$. Thus, (15) and (16) are reduced to $\frac{\partial p(x_{MM}^*)}{\partial x} z_{MM}^* + q_{MM}^* + s_{MM}^* = h'(z_{MM}^*)$ and $\frac{\partial p(x_{MM}^*)}{\partial x} y_{MM}^* + q_{MM}^* = c'(y_{MM}^*)$, respectively.

5.2 Analysis

The results of the analysis are highlighted in Propositions 4 and 5. Proposition 4 shows that the certificate market collapses in the sense that the GC price will never be established at an intermediate level. It may, however, be established at the lower or upper price bound.¹⁷

Proposition 4 *Assume that both the producers of black and green electricity act as NC-playing oligopolists in interactive electricity and GC markets, then - in equilibrium - there will i) never be established an intermediate certificate price such that $\underline{s} < s_{MM}^* < \bar{s}$, but ii) there may be an equilibrium certificate price at the lower or the upper price bound, i.e. $s_{MM}^* = \underline{s}$ or $s_{MM}^* = \bar{s}$.*

Proof. *See appendix D.* ■

In Figure 2 and 3 we illustrate the profit curves of the NC-playing producers of black and green electricity, respectively. The figures are based on a simple numerical model satisfying the assumptions of the model, see Appendix E. The profit curve of the NC-playing producers of black electricity is generated assuming that they consider both the quantity of green electricity and the number of GCs as given. Fixing the quantity of green electricity at the equilibrium level, we construct the profit curve for different quantities of black electricity. Under Cournot behavioral assumptions, oligopolistic producers of black electricity choose the quantity of black electricity that maximizes profit. The equilibrium quantity of black electricity is then found where the profit curve is at its maximum. The profit curve representing the producers of green electricity are generated analogously, i.e., assuming that these producers consider the quantity of black electricity as given.

¹⁷Observe also that the producers of green electricity will always sell all certificates generated. The proof is not included in the paper, but may be obtained from the authors upon request.

In particular, we observe the discontinuity of the profit curves. Looking first at Figure 2 we note that the profit of the producers of black electricity drops (discontinuously) at a specific value of y . This is the quantity of black electricity at which total consumption of electricity is at the allowable consumption level. For lower production levels of black electricity, there is an excess supply of GCs, i.e., the GC price is at the lower price bound. For higher production levels of black electricity, where total consumption is above the allowable consumption level, the GC price jumps to the upper price bound. Figure 2 thus illustrates an equilibrium solution with a GC price at the upper price bound. In Figure 3 we observe a similar shape in the profit curve of the producers of green electricity, i.e., the profit curve drops (discontinuously) at the point of the allowable consumption level. As opposed to the figure representing the profit curve of the producers of black electricity, quantity levels of green electricity below the allowable consumption level will generate a GC price at the *upper* price bound. For these low quantities of green electricity, there will be an excess demand for GCs. For higher quantities of green electricity, the GC price is at the lower bound. Figure 3 illustrates an equilibrium GC price at the upper price bound.

Another interesting point is that it is not necessarily the case that the producers of black electricity will always prefer a GC price at the lower price bound and the producers of green electricity prefer a GC price at the upper bound. This is illustrated by Figure 2, where the oligopolistic producers of black electricity somewhat counterintuitively maximize profit at a GC price at the upper price bound. Correspondingly, it can also be shown that the oligopolistic producers of green electricity in some cases would actually prefer a GC price at the lower price bound.

Figure 2 and 3 here

Proposition 5 verifies - as is to be expected - that market power in interactive markets leads to less total electricity generation as compared with perfect competition. Nevertheless, even though the GC system collapses under interactive market power, as shown by Proposition 4, the generation of green electricity in fact may be larger than it would be under perfect competition and therefore also - from Proposition 3 - what it would be under the standard NC-assumptions. However, the same may also be true for black electricity.

Proposition 5 *Under the assumptions of oligopolistic NC-playing producers of black and green electricity in interactive electricity and GC markets we have that i) $x_{MM}^* < x_{cc}^*$ and that ii) $\text{sign}(y_{MM}^* - y_{cc}^*)$ and $\text{sign}(z_{MM}^* - z_{cc}^*)$ are both indeterminate, irrespective of whether $\underline{s} < s_{cc}^* < \bar{s}$, $s_{cc}^* = \underline{s}$ or $s_{cc}^* = \bar{s}$.*

Proof. *See appendix F.* ■

In Figure 4 we have illustrated a number of different equilibrium solutions for different values of the percentage requirement, α . The figure is based on the numerical model specified in appendix E. The figure illustrates that the quantity of green electricity under interactive market power, z_{MM}^* , may be larger than under perfect competition, z_{cc}^* . We observe also from the figure that the quantity of black electricity in the interactive market power case, y_{MM}^* , exceeds the quantity of green electricity, i.e. we have $y_{MM}^* > z_{MM}^*$, which was shown in the proof of Proposition 5 to be a necessary condition for $z_{MM}^* > z_{cc}^*$.

Figure 4 here

6 Summary and concluding remarks

This paper examines the impact of market power in a system of Green Certificates (GCs). The results are summarized in Propositions 1-5. One of the main insights from the paper is that the

effect of market power on the GC system to a large extent depends on whether a traditional analysis using the standard Cournot framework is followed, or, and this is argued to be the more realistic case, producers are allowed to game on the *interactive* functioning of the electricity and GC markets. Under standard Cournot assumptions, the effect of market power on market prices and quantities are shown to be as expected using standard economic reasoning. However, by taking the interaction between the two markets into consideration, the results are altered significantly. Based on our analysis of market power in interactive electricity and GC markets, it seems fair to conclude that market power in most cases will prevent the realization of market-based GC price within the specified price interval. Thus, the GC system will most likely reduce to a system corresponding to direct subsidies financed through consumer/producer taxes. It is also shown that market power could affect the produced quantities of black and green electricity in unexpected ways as compared with the case of perfect competition. A third result is the uncertain impact of using the percentage requirement as a policy instrument to affect the generation of green electricity. This result applied both under perfect competition and under market power.

In the paper, we have assumed that both the producers of black and green electricity enjoy market power. An identical analysis assuming market power among only one of the generation technologies, i.e., either black or green, produced corresponding results with regard to the equilibrium GC price; the GC price will always be at one of the price bounds. The only case in which a market-based equilibrium GC price is obtained is when it is assumed that a single monopolistic producer could generate electricity from both renewable and nonrenewable sources.¹⁸

This paper also points to the increasing popularity of GC markets around the world. However,

¹⁸The proofs of these results are omitted from the text in the interests of brevity. Details of the analysis and proofs may be obtained from the authors upon request.

considering that the existence of some form of market power is not unlikely, and given the possibility of high administrative costs associated with a GC system, the problems revealed in this paper should be given serious attention. Put differently, it is unlikely to be cost efficient to introduce a GC system that ultimately functions like an ordinary subsidy scheme.

Another problematic feature of the GC system is that the percentage requirement in itself is not a policy instrument that determines the capacity level of green electricity generation (conversely to how it is commonly perceived). An increase of the percentage requirement may, in fact, lead to a reduction of remuneration through investing in new capacity for green electricity (though it will affect the composition of black and green electricity generation in the preferred direction).¹⁹ Along with other potential problems (e.g., compatibility with CO_2 -emission permits systems and strong price volatility of GCs based on wind power) the problems revealed in this paper clearly call for caution in the design and implementation of GC systems.

Empirically, experiences from GC systems actually implemented are so far limited. However, some interesting observations from the Swedish GC system may be noted. The Swedish system has been operational since May 2003. So far, the trade statistics show that GCs frequently have been traded at the specified upper GC price bound.²⁰ According to our paper, one reason for this could be market power on the supply side. Another possible explanation may be that the Swedish GCs have an unlimited durability. The upper GC price bound of the Swedish system increased from SEK 175 to SEK 240 from 2003 to 2004. This may cause market participants, consumers and producers of GCs, expecting increasing GC prices in the future, to choose to save their GCs

¹⁹ Also, the GC systems currently running or planned do not distinguish between the degree of "greenness" or "blackness". This is contrary to what a system of permits for CO_2 -emissions does.

²⁰ Trade statistics of the Swedish GC system may be obtained from the Swedish Energy Agency, <http://www.stem.se/>.

and instead pay the penalty price (consumers), or save the GCs for later sale (producers).

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Appendix

A Proof of Proposition 1

Proof. *i)* For $\underline{s} < s_{cc}^* < \bar{s}$, inserting (3) and (4) into (1) yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.

$p(x_{cc}^*) = (1 - \alpha) c'(y_{cc}^*) + \alpha h'(z_{cc}^*)$. Take the implicit derivatives of this expression with respect to α and arrive at: $\frac{dz_{cc}^*}{d\alpha} = \frac{\alpha s_{cc}^* + x_{cc}^* [(\partial p / \partial x) - (1 - \alpha) c''(y_{cc}^*)]}{D}$, $\frac{dy_{cc}^*}{d\alpha} = \frac{(1 - \alpha) s_{cc}^* + x_{cc}^* [\alpha h''(z_{cc}^*) - (\partial p / \partial x)]}{D}$, and $\frac{dx_{cc}^*}{d\alpha} = \frac{s_{cc}^* + x_{cc}^* [\alpha h''(z_{cc}^*) - (1 - \alpha) c''(y_{cc}^*)]}{D}$, with $D = \left[\frac{\partial p}{\partial x} - (1 - \alpha)^2 c''(y_{cc}^*) - \alpha^2 h''(z_{cc}^*) \right] < 0$. Inspection of signs verifies the above claims.

ii) For $s_{cc}^* = \underline{s}$ or $s_{cc}^* = \bar{s}$, insert (4) in (3). Take the implicit derivative with respect to α and get $h''(z_{cc}^*) \frac{dz_{cc}^*}{d\alpha} = c''(y_{cc}^*) \frac{dy_{cc}^*}{d\alpha}$. As marginal costs are assumed increasing it follows: $\text{sign} \frac{dz_{cc}^*}{d\alpha} = \text{sign} \frac{dy_{cc}^*}{d\alpha} = \text{sign} \frac{dx_{cc}^*}{d\alpha}$. The last equality follows as $\frac{dx_{cc}^*}{d\alpha} = \frac{dz_{cc}^*}{d\alpha} + \frac{dy_{cc}^*}{d\alpha}$. But the signs cannot be non-negative. To see this insert (4) in (1) and take the implicit derivative with respect to α to obtain $\frac{\partial p}{\partial x} \frac{dx_{cc}^*}{d\alpha} = c''(y_{cc}^*) \frac{dy_{cc}^*}{d\alpha} + \tilde{s}$, where $\tilde{s} = \bar{s}$ or \underline{s} . As $\frac{\partial p}{\partial x} < 0$ we must have $\frac{dx_{cc}^*}{d\alpha} < 0$ for this equation to hold. Hence, $\text{sign} \frac{dz_{cc}^*}{d\alpha} = \text{sign} \frac{dy_{cc}^*}{d\alpha} = \text{sign} \frac{dx_{cc}^*}{d\alpha} < 0$ for this case. ■

B Proof of Proposition 2

Proof. *i)* For $\underline{s} < s_{mm}^* < \bar{s}$, inserting (7) and (8) into (1) yields the electricity price as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.

$p(x_{mm}^*) = (1 - \alpha) \left[c'(y_{mm}^*) - \frac{\partial p}{\partial x} y_{mm}^* \right] + \alpha \left[h'(z_{mm}^*) - \frac{\partial p}{\partial x} z_{mm}^* \right]$. Take the implicit derivatives of this expression with respect to α and arrive at:

$$\frac{dz_{mm}^*}{d\alpha} = \frac{x_{mm}^* \left[p'(x_{mm}^*) + (1 - \alpha) p'(x_{mm}^*) + (1 - \alpha) p''(x_{mm}^*) y_{mm}^* - \alpha p''(x_{mm}^*) z_{mm}^* - (1 - \alpha) c''(y_{mm}^*) \right]}{F} +$$

$$\frac{\alpha \left[p'(x_{mm}^*) y_{mm}^* - c'(y_{mm}^*) + h'(z_{mm}^*) - p'(x_{mm}^*) z_{mm}^* \right]}{F},$$

$$\frac{dy_{mm}^*}{d\alpha} = \frac{\alpha q_{mm}^* + s_{mm}^* + x_{mm}^* [\alpha h''(z_{mm}^*) - (1-\alpha)p'(x_{mm}^*) - \alpha p''(x_{mm}^*)z_{mm}^*] - p''(x_{mm}^*)y_{mm}^*}{F}, \text{ and}$$

$$\frac{dx_{cc}^*}{d\alpha} = \frac{x_{mm}^* [(1-\alpha)p'(x_{mm}^*) - (1-\alpha)c''(y_{mm}^*) + \alpha h''(z_{mm}^*) - \alpha p'(x_{mm}^*)]}{F} -$$

$$\frac{p'(x_{mm}^*)y_{mm}^* - p'(x_{mm}^*)z_{mm}^* - c'(y_{mm}^*) + h'(z_{mm}^*)}{F}, \text{ with}$$

$$F = \left[\begin{array}{l} p'(x_{mm}^*) - (1-\alpha)^2 c''(y_{mm}^*) - \alpha^2 h''(z_{mm}^*) + (1-\alpha)p''(x_{mm}^*)y_{mm}^* \\ + (1-\alpha)^2 p'(x_{mm}^*) + \alpha p''(x_{mm}^*)z_{mm}^* + \alpha^2 p'(x_{mm}^*) \end{array} \right] < 0,$$

given $p''(x_{mm}^*) \leq 0$. Inspection of signs verifies the above claims, given $p''(x_{mm}^*) \leq 0$.

ii) For $s_{mm}^* = \underline{s}$ or $s_{mm}^* = \bar{s}$, insert (8) in (7). Take the implicit derivative with respect to α

$$\text{and get } h''(z_{mm}^*) \frac{dz_{cc}^*}{d\alpha} = c''(y_{mm}^*) \frac{dy_{mm}^*}{d\alpha} + p'(x_{mm}^*) \left[\frac{\partial z_{mm}^*}{\partial \alpha} - \frac{\partial y_{mm}^*}{\partial \alpha} \right] + p''(x_{mm}^*) \frac{dx_{mm}^*}{d\alpha} [z_{mm}^* - y_{mm}^*].$$

Assume first linear demand, i.e. $p''(x_{mm}^*)$, then as marginal costs are assumed increasing it

follows: $\text{sign} \frac{dz_{mm}^*}{d\alpha} = \text{sign} \frac{dy_{mm}^*}{d\alpha} = \text{sign} \frac{dx_{mm}^*}{d\alpha}$. The last equality follows as $\frac{dx_{mm}^*}{d\alpha} = \frac{dz_{mm}^*}{d\alpha} + \frac{dy_{mm}^*}{d\alpha}$.

But the signs cannot be non-negative. To see this insert (8) in (5) and take the implicit derivative

$$\text{with respect to } \alpha \text{ to obtain } p'(x_{mm}^*) \left[\frac{dx_{mm}^*}{d\alpha} - \frac{dy_{mm}^*}{d\alpha} \right] = c''(y_{cc}^*) \frac{dy_{mm}^*}{d\alpha} + \tilde{s}, \text{ where } \tilde{s} = \bar{s} \text{ or } \underline{s}. \text{ As}$$

$p'(x) < 0$ we must have $\frac{dx_{mm}^*}{d\alpha} < 0$ for this equation to hold. Hence, $\text{sign} \frac{dz_{mm}^*}{d\alpha} = \text{sign} \frac{dy_{mm}^*}{d\alpha} =$

$\text{sign} \frac{dx_{mm}^*}{d\alpha} < 0$ for this case. ■

C Proof of Proposition 3

Proof. To obtain a contradiction assume $z_{mm}^* \geq z_{cc}^*$. As $z_{mm}^* = \frac{\alpha}{1-\alpha} y_{mm}^* = \alpha x_{mm}^*$ (from (6)) and

$z_{cc}^* = \frac{\alpha}{1-\alpha} y_{cc}^* = \alpha x_{cc}^*$ (from (2)); we see that $z_{mm}^* \geq z_{cc}^*$ implies $y_{mm}^* \geq y_{cc}^*$ and $x_{mm}^* \geq x_{cc}^*$. Hence,

we must have $p(x_{mm}^*) \leq p(x_{cc}^*)$. Next, from (8) and (4) we have $q_{mm}^* = c'(y_{mm}^*) - p'(x_{mm}^*)y_{mm}^*$

and $q_{cc}^* = c'(y_{cc}^*)$. As $z_{mm}^* \geq z_{cc}^*$ implies $y_{mm}^* \geq y_{cc}^*$ we must have $q_{mm}^* > q_{cc}^*$. Next, by successive

substitutions from the two sets of first order conditions we arrive at $p(x_{mm}^*) = (1-\alpha)q_{mm}^* +$

$\alpha [h'(z_{mm}^*) - p'(x_{mm}^*)z_{mm}^*]$ and $p(x_{cc}^*) = (1-\alpha)q_{cc}^* + \alpha [h'(z_{cc}^*)]$. As $q_{mm}^* > q_{cc}^*$ and $z_{mm}^* > z_{cc}^*$,

we are forced to conclude that $p(x_{mm}^*) > p(x_{cc}^*)$. This contradicts the above conclusion that

$p(x_{mm}^*) \leq p(x_{cc}^*)$. Hence, we must have $z_{mm}^* < z_{cc}^*$ and $y_{mm}^* < y_{cc}^*$. ■

D Proof of Proposition 4

Proof. This proof consists of two parts. *i)* Assume first that we look at the quantity decision from the point of view of the producers of black electricity. To show that we cannot have $\underline{s} < s_{mm}^* < \bar{s}$, assume \hat{y} is a solution satisfying the first order conditions for the producers of black electricity and that $\hat{y} + \bar{z} = \frac{\bar{z}}{\alpha}$ where \bar{z} is the quantity of green electricity that the producers of black electricity, in accordance with the NC-assumption, consider as given. Clearly, if $y < \hat{y}$, then $s_{mm}^* = \underline{s}$, due to excess supply of certificates (i.e. $\bar{z} > \alpha(y + \bar{z})$) and if $y > \hat{y}$, then $s_{mm}^* = \bar{s}$, due to excess demand for certificates. Denote the marginal revenue function, $g(y, \bar{z})$, by $g(y, \bar{z}) = \frac{\partial q}{\partial y}y + q$. Observe that $g(y, \bar{z}) = \frac{\partial p}{\partial x}y + q$ for $y \neq \hat{y}$ as $\frac{\partial s}{\partial y} = 0$ for such values. Clearly, $g(y, \bar{z})$ is discontinuous at \hat{y} as $\lim_{y \rightarrow \hat{y}^-} g(y, \bar{z}) = \frac{\partial p}{\partial x}\hat{y} + \hat{q}^-$ and $\lim_{y \rightarrow \hat{y}^+} g(y, \bar{z}) = \frac{\partial p}{\partial x}\hat{y} + \hat{q}^+$ where $\hat{q}^- = \lim_{y \rightarrow \hat{y}^-} q = p(\hat{y} + \bar{z}) - \alpha\underline{s}$ and $\hat{q}^+ = \lim_{y \rightarrow \hat{y}^+} q = p(\hat{y} + \bar{z}) - \alpha\bar{s}$. However, as $\Pi(\hat{y}, \bar{z}) = q\hat{y} - c(\hat{y})$, profit maximization will lead the producers of black electricity to secure \hat{q}^- (by an infinitesimal quantity reduction of black electricity) implying the corner solution, i.e. $s_{mm}^* = \underline{s}$. An example is illustrated in Figure 2.

ii) Then we focus on the problem from the point of view of the producers of green electricity. To show that we cannot have $\underline{s} < s_{mm}^* < \bar{s}$, assume \hat{z} and \hat{w} , with $\hat{w} \leq \hat{z}$, satisfy the optimality conditions for the producers of green electricity and that $\bar{y} + \hat{z} = \frac{\hat{w}}{\alpha}$ where \bar{y} is the quantity of black electricity that the producers of green electricity, in accordance with the NC-assumption, consider as given. We consider two cases: a) $\hat{w} < \hat{z}$ and b) $\hat{w} = \hat{z}$.

a) Clearly, if $z < \hat{z}$ (for given values of \bar{y} and \hat{w}) then $s_{mm}^* = \underline{s}$, due to excess supply of certificates (i.e. $\hat{w} > \alpha(\bar{y} + z)$) and if $z > \hat{z}$, then $s_{mm}^* = \bar{s}$, due to excess demand for certificates. Denote the marginal revenue function, $g(z, \bar{y}, \hat{w})$, by $g(z, \bar{y}, \hat{w}) = \frac{\partial q}{\partial z}z + \frac{\partial s}{\partial z}\hat{w} + q$. Observe that

$g(z, \bar{y}, \hat{w}) = \frac{\partial p}{\partial x} z + q$ for $z \neq \hat{z}$ as $\frac{\partial s}{\partial z} = 0$ for such values. Clearly, $g(z, \bar{y}, \hat{w})$ is discontinuous at \hat{z} as $\lim_{z \rightarrow \hat{z}^-} g(z, \bar{y}, \hat{w}) = \frac{\partial p}{\partial x} \hat{z} + \hat{q}^-$ and $\lim_{z \rightarrow \hat{z}^+} g(z, \bar{y}, \hat{w}) = \frac{\partial p}{\partial x} \hat{z} + \hat{q}^+$ where $\hat{q}^- = \lim_{z \rightarrow \hat{z}^-} q = p(\bar{y} + \hat{z}) - \alpha \underline{s}$ and $\hat{q}^+ = \lim_{z \rightarrow \hat{z}^+} q = p(\bar{y} + \hat{z}) - \alpha \bar{s}$. The profit function is $\Pi(\hat{z}, \bar{y}, \hat{w}) = q\hat{z} + s\hat{w} - h(\hat{z})$. Rewrite this as $\Pi(\hat{z}, \bar{y}, \hat{w}) = p(\bar{y} + \hat{z})\hat{z} + s(\hat{w} - \alpha\hat{z}) - h(\hat{z})$ and observe that the assumption of $\bar{y} + \hat{z} = \frac{\hat{w}}{\alpha}$ implies $\hat{w} > \alpha\hat{z}$. Hence, profit maximization will lead the producers of green electricity to secure \hat{q}^+ (by an infinitesimal quantity increase of green electricity) implying the corner solution $s_{mm}^* = \bar{s}$. An example is illustrated in figure 3. ■

E Proof of Proposition 5

Proof. *i)* To obtain a contradiction, assume that $x_{MM}^* \geq x_{cc}^*$, then we must have either $y_{MM}^* \geq y_{cc}^*$ or $z_{MM}^* \geq z_{cc}^*$ or both $y_{MM}^* \geq y_{cc}^*$ and $z_{MM}^* \geq z_{cc}^*$. Assume $y_{MM}^* \geq y_{cc}^*$, then $q_{MM}^* = c'(y_{MM}^*) - \frac{\partial p}{\partial x} y_{MM}^* > c'(y_{cc}^*) = q_{cc}^*$. Consider the case of $s_{MM}^* = \bar{s}$ and $\underline{s} \leq s_{MM}^* \leq \bar{s}$ and the case of $s_{MM}^* = \underline{s}$ and $s_{cc}^* = \underline{s}$. From (1) and (9) we have $p(x_{MM}^*) = q_{MM}^* + \alpha s_{MM}^* > q_{cc}^* + \alpha s_{cc}^* = p(x_{cc}^*)$. Hence, $x_{MM}^* < x_{cc}^*$. This contradicts the assumption that $x_{MM}^* \geq x_{cc}^*$. It remains to consider the case of $s_{MM}^* = \underline{s}$ and $s_{cc}^* > \underline{s}$. As $s_{MM}^* = \underline{s}$ we know that $z_{MM}^* > \alpha x_{MM}^*$ and as $s_{cc}^* > \underline{s}$ we know that $z_{cc}^* > \alpha x_{cc}^*$. Under the assumption that $x_{MM}^* \geq x_{cc}^*$ we must thus have $z_{MM}^* \geq z_{cc}^*$. From (3) and (11) we then have $q_{MM}^* + \underline{s} > q_{MM}^* + \frac{\partial p}{\partial x} z_{MM}^* + \underline{s} = h'(z_{MM}^*) > h'(z_{cc}^*) = q_{cc}^* + s_{cc}^*$. Furthermore, we have $q_{MM}^* - q_{cc}^* > s_{cc}^* - \underline{s} > \alpha s_{cc}^* - \alpha \underline{s} > 0$. Hence, we must also have $p(x_{MM}^*) = q_{MM}^* + \alpha \underline{s} > q_{cc}^* + \alpha s_{cc}^* = p(x_{cc}^*)$. Consequently, $x_{MM}^* < x_{cc}^*$, which contradicts the assumption that $x_{MM}^* \geq x_{cc}^*$. Hence, we must have $x_{MM}^* < x_{cc}^*$. Alternatively we may reach the same conclusion starting with the assumption that $z_{MM}^* \geq z_{cc}^*$.

ii) However, we may have $y_{MM}^* \geq y_{cc}^*$ or $z_{MM}^* \geq z_{cc}^*$ provided that z_{MM}^* is sufficiently smaller than z_{cc}^* , or y_{MM}^* is sufficiently smaller than y_{cc}^* , such that $x_{MM}^* < x_{cc}^*$ is still satisfied.

a) Consider first a sufficient condition for $z_{MM}^* \geq z_{cc}^*$: from (3) and (7) we see that if $q_{MM}^* + \frac{\partial p}{\partial x} z_{MM}^* + s_{MM}^* \geq q_{cc}^* + s_{cc}^*$ then $h'(z_{MM}^*) \geq h'(z_{cc}^*)$ so that $z_{MM}^* \geq z_{cc}^*$. Substituting from (4) and (8) we have $c'(y_{MM}^*) + \frac{\partial p}{\partial x} (z_{MM}^* - y_{MM}^*) + s_{MM}^* \geq c'(y_{cc}^*) + s_{cc}^*$. From *i*) we have that $z_{MM}^* \geq z_{cc}^*$ implies $y_{MM}^* < y_{cc}^*$. Thus, $\frac{\partial p}{\partial x} (z_{MM}^* - y_{MM}^*) + s_{MM}^* - s_{cc}^* \geq c'(y_{cc}^*) - c'(y_{MM}^*) \geq 0$. For the cases of $s_{cc}^* \geq s_{MM}^*$, we see that this condition necessitates $y_{MM}^* > z_{MM}^*$. If $c''(y) = 0$ and $s_{cc}^* \geq s_{MM}^*$ then $y_{MM}^* > z_{MM}^*$, i.e. black electricity has more than 50% of the market, is alone a sufficient condition for $z_{MM}^* \geq z_{cc}^*$.

b) Next, consider a sufficient condition for $y_{MM}^* \geq y_{cc}^*$. From (4) and (8) we see that if $q_{MM}^* + \frac{\partial p}{\partial x} y_{MM}^* \geq q_{cc}^*$ then $c'(y_{MM}^*) \geq c'(y_{cc}^*)$ so that $y_{MM}^* \geq y_{cc}^*$. Substituting from (3) and (7), rearranging terms and recognizing from *i*) that $y_{MM}^* \geq y_{cc}^*$ implies $z_{MM}^* < z_{cc}^*$ we get $\frac{\partial p}{\partial x} (y_{MM}^* - z_{MM}^*) + s_{cc}^* - s_{MM}^* \geq h'(z_{cc}^*) - h'(z_{MM}^*) \geq 0$. For cases of $s_{MM}^* \geq s_{cc}^*$ we see that this condition necessitates $z_{MM}^* \geq z_{cc}^*$. If $h''(z) = 0$ and $s_{MM}^* \geq s_{cc}^*$ then $z_{MM}^* \geq y_{MM}^*$, i.e. green electricity has more than 50% of the market, is alone a sufficient condition for $y_{MM}^* > y_{cc}^*$. ■

F 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 is used to provide proofs for the existence of some of the results referred to in the propositions in this article. It is also applied for the calculations of the numerical examples illustrated by Figures 2-7.

We assume the following functions:

The inverse demand function is given by:

$$p(x) = a - bx, \text{ with } a, b > 0.$$

This gives:

$$p'(x) = -b < 0.$$

The technology for generation of black electricity is summarized in the cost function:

$$c(y) = \frac{1}{2}y^2, \text{ with } c'(y) = y > 0 \text{ and } c''(y) = 1 \geq 0.$$

The producers of green electricity have the following cost function:

$$h(z) = \frac{c}{2}z^2 + gz, \text{ where } c, g > 0, \text{ with } h'(z) = cz + g > 0 \text{ and } h''(z) = c \geq 0.$$

Details of the numerical examples are not included in this paper, but may be obtained from the authors upon request.

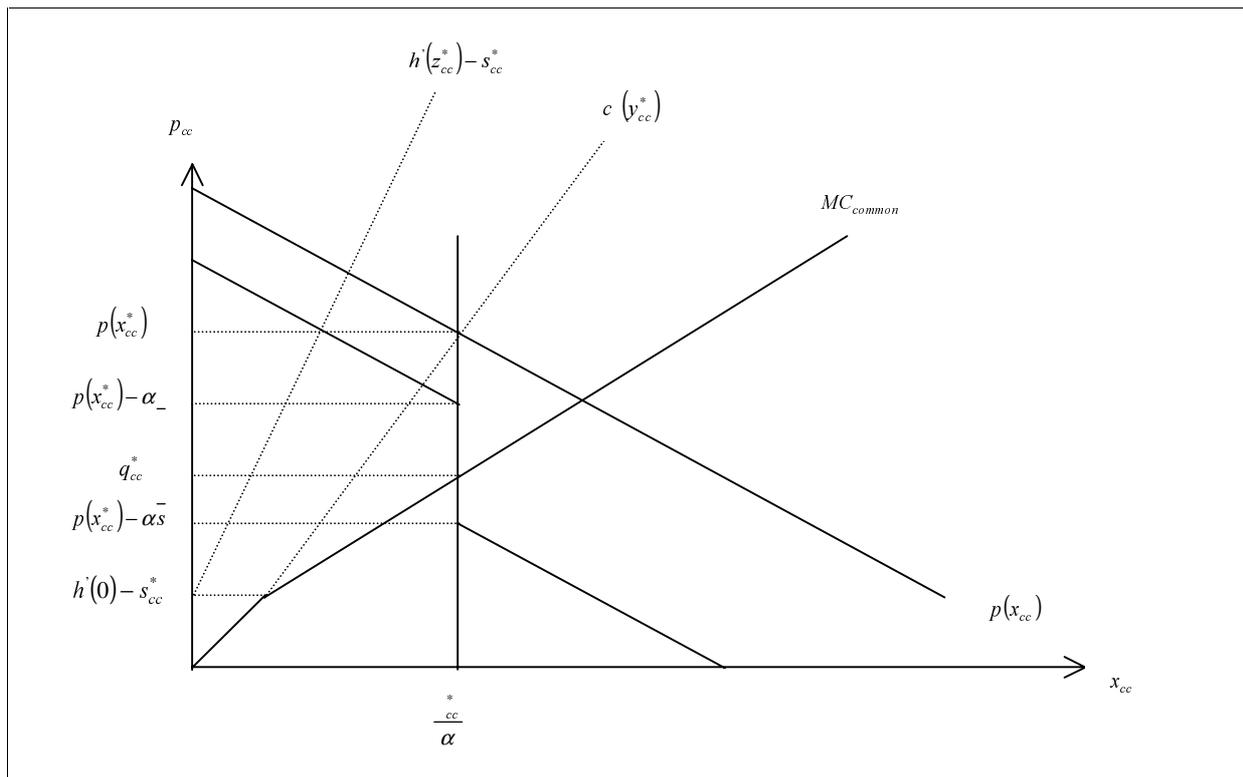


Figure 1: Illustration of the cc-equilibrium for the case of an interior GC-price.

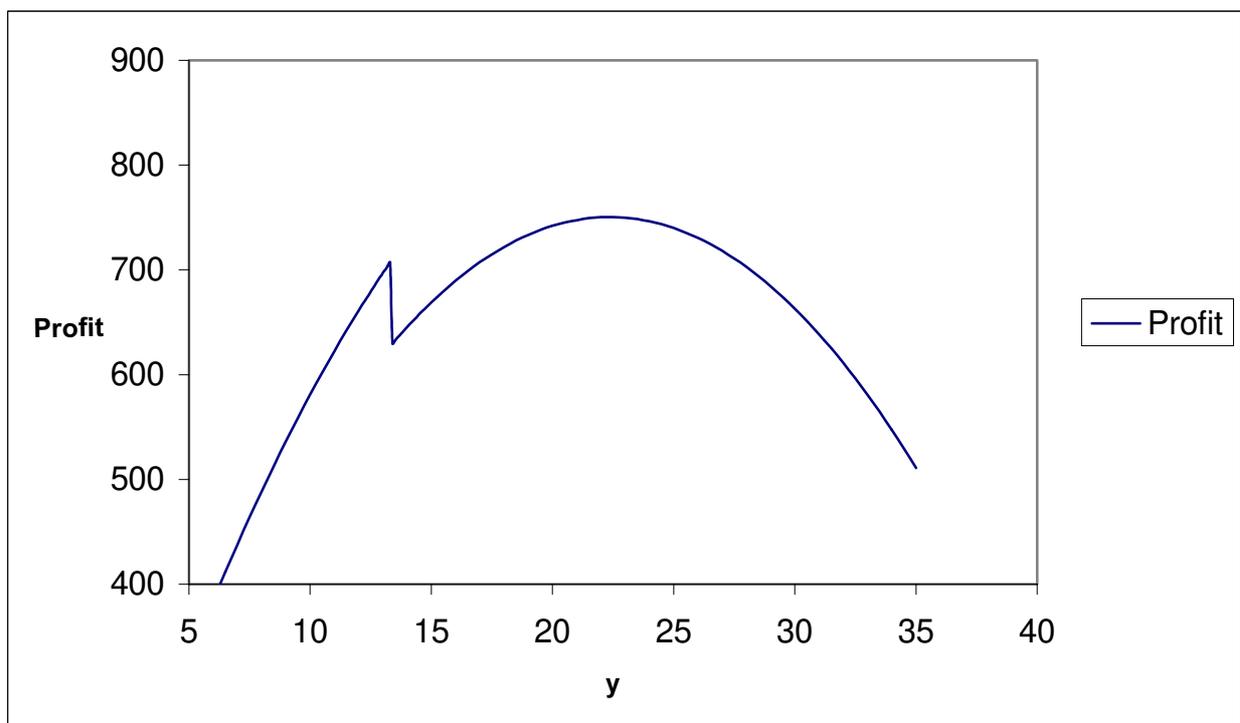


Figure 2: Profit curve for the oligopolistic producers of black electricity in the interactive market power case, illustrating an equilibrium GC-price at the upper price bound. (The figure is based on the following parameter values used in the numerical model: $\alpha = 0.6$, $a = 100$, $b = 1$, $c = 2$, $g = 5$, $\bar{s} = 25$, $\underline{s} = 10$)

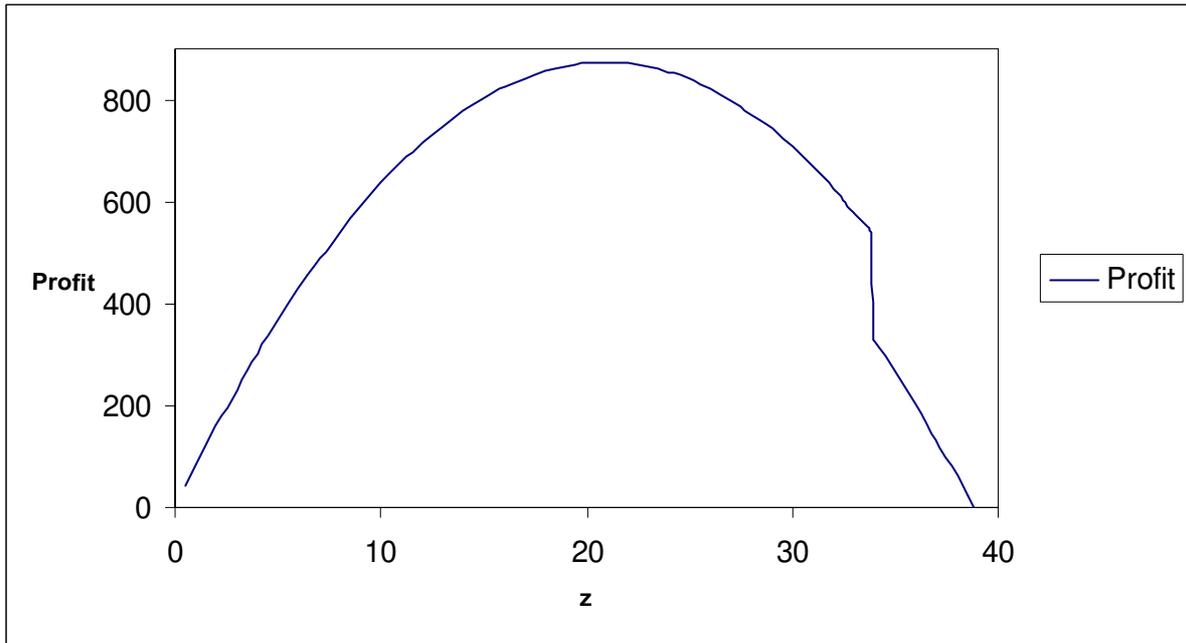


Figure 3: Profit curve for the oligopolistic producers of green electricity in the interactive market power, illustrating an equilibrium GC-price at the upper price bound. (The figure is based on the following parameter values used in the numerical model: $\alpha = 0.6$, $a = 100$, $b = 1$, $c = 2$, $g = 5$, $\bar{s} = 25$, $\underline{s} = 10$)

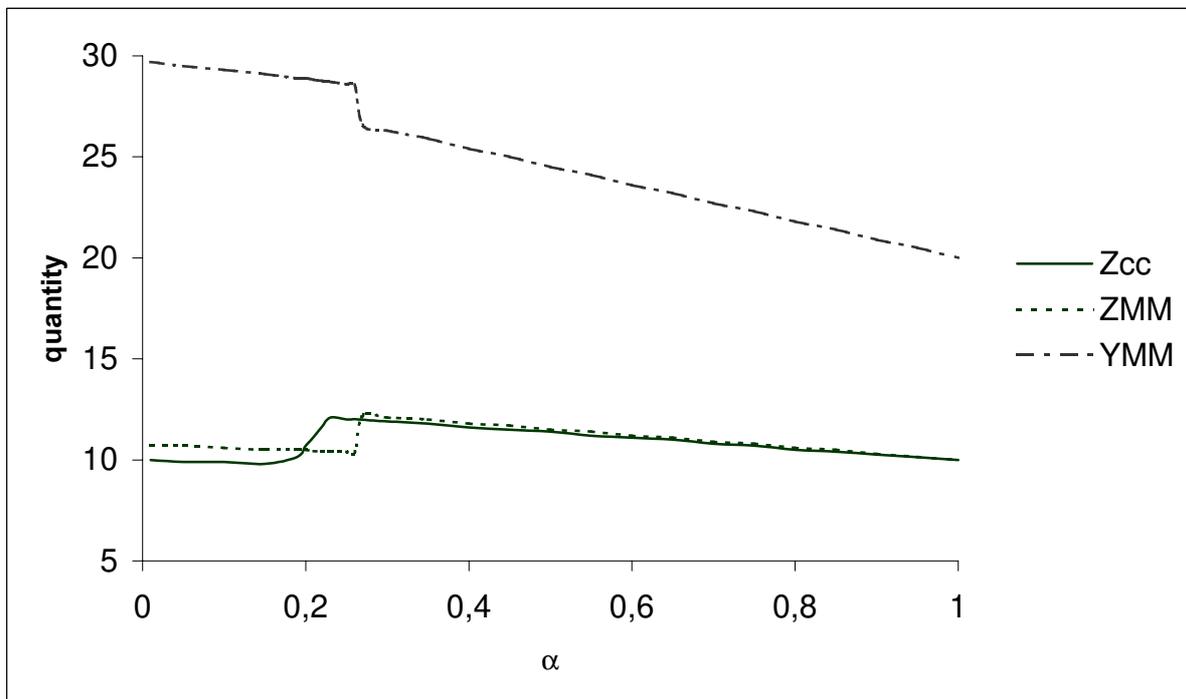


Figure 4: Equilibrium quantities of green electricity under perfect competition and equilibrium quantities of both black and green electricity in the interactive market power case for different values of the percentage requirement. (The figure is based on the following parameter values used in the numerical model: $a = 100$, $b = 1$, $c = 5$, $g = 10$, $\bar{s} = 30$, $\underline{s} = 15$)

Department of Economics
University of Bergen
Fosswinckels gate 6
N-5007 Bergen, Norway
Phone: +47 55 58 92 00
Telefax: +47 55 58 92 10
<http://www.svf.uib.no/econ>