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

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Abstract

A market for Tradable Green Certificates (TGCs) is strongly interwoven in the electricity market as the producers of green electricity are also the suppliers of TGCs. Therefore, strategic interaction may result. We formulate an analytic equilibrium model for simultaneously functioning electricity and TGC markets, and focus on the role of market power (i.e. Stackelberg leadership). One result is that a certificate system faced with market power may collapse into a system of per unit subsidies. Also, the model shows that TGCs may be an imprecise instrument for regulating the generation of green electricity. (JEL: C7; Q28; Q42; Q48)

1 Introduction

Along with the pursuance of targets for renewable energy production many developed economies (e.g. Norway, Sweden, UK, US) have implemented systems of tradable green certificates (TGCs)[1]. In brief, a TGC market consists of sellers and buyers of TGCs. The sellers are the producers of electricity using renewable sources (green electricity). These producers are each issued a number of TGCs 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 TGCs ("the percentage requirement") corresponding to their total consumption/end-use deliveries of electricity.[2] The TGCs are then seen as permits for consuming electricity. Accordingly, this system implies that the producers of green electricity receive both the wholesale price and the value of a TGC for each kWh fed into the electricity network. In this manner, the TGC system is supposed to stimulate new investments in green electricity generation.

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[1] These are also referred to as Renewable Obligation Certificates (UK) or Renewable Portfolio Standards (US).

[2] Italy 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 TGC system is that the percentage requirement functions as a check on total electricity consumption, as the total number of TGCs available is constrained by the total capacity of renewable technologies.[3] For instance, a requirement of 20 percent 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 TGC system may include a lower price bound, at which level the authorities guarantee to purchase any excess supply of TGCs. 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 generation[4].

Up until now several aspects of the general functioning of TGC markets have been investigated. For example, problems relating to the TGC market as an instrument for inducing new capacity for green electricity production and problems related to the TGC markets acting in concert with electricity markets and CO_2 markets have been studied, see e.g. Amundsen and Mortensen (2001, 2002), Bye (2003), Butler and Neuhoff (2008), Traber and Kemfert (2009), Fischer (2009) and Bøhringer and Rosendahl (2010). Along with this also the question of market power has been dealt with, see e.g. Montero (2009) and Amundsen and Bergman (2012). However, yet another problematic feature related to market power needs to be investigated. More precisely, a problem emerges as electricity producers possessing market power take account of the joint functioning of the electricity market and the TGC market. As will be shown later, this may result in a collapse of the pricing mechanism of the TGC system as the TGC price cannot be established between the price bounds, i.e. if an equilibrium exisits it must be 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.[5]

In a competitive setting, the TGC system may function as an ordinary market determining TGC prices somewhere intermediate to the upper and lower price bounds. The same may be true for a pure monopoly where the single producer generates both green and black electricity. However, this may no longer be so in the face of market power, where companies specialize in either green or black electricity. Hence, in this setting, if major electricity producers conjecture the impact on the TGC price of their production decisions in the electricity market and take account of this, then the TGC pricing mechanism may break down. By withholding electricity delivered to the wholesale market, the electricity producer can exercise market power by either forcing the TGC 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 TGCs is created (leading to a price at the upper price bound and the lower price bound,

[3]However, in 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 annual variations in the total production of green electricity and, therefore also, of TGCs issued.

[4]The Swedish TGC system became effective as of May 1 2003, while the The Norwegian- Swedish TGC system became operational from 1. January, 2012. The Swedish percentage requirement for 2012 was set at 17.9 percent while the Norwegian was set at 3 percent. In 2020 both percentages is set close to a maximum at around 18 percent. Therafter, the percentage requirements will fall towards zero in 2035.

[5]In particular, Chen and Hobbs (2005) 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.

respectively, with corresponding opposite effects on the wholesale prices). These results are valid irrespective of whether it is the producers of green or black electricity (electricity based on non renewable sources), or both, that possess market power. Thus, the TGC market may collapse altogether into a system of fixed TGC prices instead of endogenously determined intermediate prices.[6] In that case the TGC system may equally well be replaced by a plain subsidy scheme for green electricity, with presumably much lower transaction costs and more precise effects on green power capacity construction.

The problem of interactive power and TGC markets is then germane since the TGC 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 TGC 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 percent) of the TGC price. Hence, the revenue of a major producer of green electricity stems from both markets (i.e., the electricity wholesale price and the TGC 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 TGCs). Furthermore, a major producer of black electricity knows (even though not directly involved in TGC 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 TGCs.

Market power in electricity generation is likely to exist in many economies. In 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 (Olsen et al., 2006). Hence, the possible malfunctioning of the pricing mechanism pointed to above should be given serious consideration in the discussions and development of alternative TGC systems.

In the following, we formulate an analytic equilibrium model for a TGC system and consider three main cases: a) Perfect competition in both the electricity market and the TGC market, b) Pure monoply with joint generation of green and black electricity, and c) Stackelberg setting consisting of a leader specialized in the generation of black electricity and a follower specialized in the generation of green electricity. 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 the paper.

2 The model

The following model is designed to capture a setting of simultaneously functioning electricity and TGC markets. We will use the following symbols for the variables involved:

p = consumer price of electricity
s = price of TGCs
$\overline{s}$ = upper price bound of TGCs
$\underline{s}$ = lower price bound of TGCs
q = wholesale price of electricity
x = total consumption of electricity
y = generation of black electricity
z = generation of green electricity and equal to number of TGCs issued

[6]It is interesting to note that during the first year of the Swedish TGC system, TGCs have frequently been traded at prices equal to the upper price bound, see Stem (2005).

$\alpha =$ percentage requirement of green electricity consumption

$g_d =$ demand for TGCs

The inverse demand function is assumed given by:[7]

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

The intermediate or long run industry cost function for black electricity is assumed given by[8]:

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

The rationale for choosing a marginal cost function that is increasing 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 corresponding industry cost function for green electricity is assumed given by:[9]

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

The rationale for choosing a marginal cost function that is increasing for this industry, is that good sites for generation technologies such as wind-mills may be in scarce supply, wherefore an expansion of green electricity generation implies increasing costs. On the other hand, learning by doing effects may well lead to reduced generation costs for green electricity over time, see Søderholm and Sundqvist (2003), wherefore this assumption may not seem so realistic after all. However, the specified cost function may be seen as relevant for the medium term as the full result of learning by doing effects will only materialize in the longer term.

3 Perfect competition

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

The producers act as if they jointly maximize:[10]

$\Pi(x) = q(z,y)y + [q(z,y) + s(z,y)]\,z - c(y) - h(z).$

The first-order condition for black electricity generation is:

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

The first-order condition for green electricity generation is:

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

We assume that a TGC is measured in the same unit as electricity (i.e. MWh).With the given percentage requirement, α, retailers have to purchase an α-share of a TGC for each unit of electricity (whether black or green) delivered to the end users. Thus, total demand for TGCs is given by $g_d = \alpha x$,whereas total supply of TGCs is equal to the amount of green electricity

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

[8] For a short-run version of the competitive model, see Amundsen and Mortensen (2001).

[9] In the short run with sunk cost capital equipment, marginal cost of green electricity may be close to zero, see e.g. Amundsen and Mortensen (2001). In the intermediate or long run situation considered here, however, capital costs are included.

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

generated, z. For each unit of electricity (i.e., each MWh) purchased in the wholesale market and sold on to end users, retailers have to pay the wholesale price plus a share, α, of the TGC price. For simplicity, electricity distribution is assumed to be costless. With a large number of retailers, the equilibrium established in the market (i.e., the competitive equilibrium) must be characterized by:

$p(x) = q(z, y) + \alpha s(z, y)$, where $x = z + y$

3.1 Equilibrium under perfect competition

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

$$p\left(x_C^*\right) = q_C^* + \alpha s_C^* \quad (1)$$

$$x_C^* = y_C^* + z_C^* < \frac{z_C^*}{\alpha}, \text{ or } x_C^* = y_C^* + z_C^* = \frac{z_C^*}{\alpha}, \text{ or } x_C^* = y_C^* + z_C^* > \frac{z_C^*}{\alpha} \quad (2)$$

$$q_C^* + s_C^* = h^{'}\left(z_C^*\right) \quad (3)$$

$$q_C^* = c^{'}\left(y_C^*\right) \quad (4)$$

From (2), if there is an excess supply of TGCs, i.e. $\alpha x_C^* < z_C^*$, then $s_C^* = \underline{s}$, and if there is an excess demand for TGCs. i.e. $\alpha x_C^* > z_C^*$,then $s_C^* = \overline{s}$. Otherwise if TGC demand is equal to TGC supply, i.e. $\alpha x_C^* = z_C^*$, then $\underline{s} < s_C^* < \overline{s}$. Basically, the quantity constraint implied by the percentage requirement drives a wedge equal to αs_C^* 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. Furthermore, by substituting (2), (3), and (4) into (1), we find that $p\left(x_C^*\right) = (1-\alpha)c'(y_C^*) + \alpha h'(z_C^*)$ i.e. in the competitive equilibrium, the consumer price of electricity is equal to a linear combination of the marginal cost of black and green electricity with the percentage requirement as a weight.

3.2 Analysis

In the TGC system, 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 erroneous to believe that a harsher percentage requirement necessarily will result in an increased capacity of green electricity generation. 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 consumer price is also indeterminate. Note that the TGC 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.[11]

Proposition 1 *Under perfect competition in the electricity and the certificate markets, the percentage requirement, α, has the following effects on the total electricity consumption x_C^* and the green electricity generation z_C^* : i) if $\underline{s} < s_C^* < \overline{s}$, then $(dy_C^*/d\alpha) < 0$ while sign $(dz_C^*/d\alpha)$ and sign $(dx_C^*/d\alpha)$ are indeterminate, and ii) if $s_C^* = \overline{s}$ or $s_C^* = \underline{s}$, then $(dz_C^*/d\alpha) < 0$, $(dy_C^*/d\alpha) < 0$,$(dx_C^*/d\alpha) < 0$.*

Proof. *See appendix A.* ■

As shown in proposition 1, the effect on total electricity consumption of changing the percentage requirement is generally indeterminate. However, if the marginal cost of black electricity is constant (i.e.$\left(\partial^2 c/\partial y^2\right) = 0$), we find that $(dx_C^*/d\alpha) < 0$. Thus, an increase of the percentage requirement will lead to a reduction of total electricity consumption. However, the impact on green electricity generation remains indeterminate. In addition, the effects depend on the level of the percentage requirement, α. For example, if $\alpha = 0$, then $(dz_C^*/d\alpha) > 0$, whereas $(dx_C^*/d\alpha)$ is indeterminate.

4 Monopoly

As another reference case, in addition to the case of pure competition, we consider the case of a pure monopoly with a single producer generating both green and black electricity. We assume that the monopolist seeks to maximize the following objective function:

$\Pi(z, y) = q(z, y)x + s(z, y)z - h(z) - c(y)$

While recognizing that $q(z, y) = p(x) - \alpha s(z, y)$,we arrive at the following first order conditions:

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

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

Observe that the second expressions on the left hand side of the equality sign of these two expressions are always zero. If $\alpha x > z$, then $s = \overline{s}$,and if $\alpha x < z$, then $s = \underline{s}$. As $\overline{s}$ and $\underline{s}$ are constants, we have[12] $(\partial\overline{s}/\partial z) = (\partial\overline{s}/\partial y) = (\partial\underline{s}/\partial z) = (\partial\underline{s}/\partial y) = 0$. If $\alpha x = z$, then these expressions are also equal to zero.

The equilibrium conditions for a pure monopoly (key variables denoted by $*$ and subscript M) are as follows:

[11] This is a generalization of results obtained in Amundsen and Mortensen (2001, 2002).

[12] Note that $(\partial s/\partial y) = 0$ and $(\partial s/\partial z) = 0$ at the TGC price bounds requires that the quantities of black and green electricity are sufficiently above or below the limits leading to either an excess or deficit supply of green electricity i.e. $\alpha x << z$ or $\alpha x >> z$. If this is not the case, then a marginal increase in z or y will induce a jump either up or down between the price bounds. Hence, if there is a sufficiently small excess supply of TGCs, thus giving rise to $s^* = \underline{s}$, then a marginal reduction of z, will induce a jump of the TGC price from $\underline{s}$ to $\overline{s}$, and $(\partial s/\partial y)$ and$(\partial s/\partial z)$ would not be defined as the marginal revenue would be discontinous at this point. Throughout our analysis we will assume that the quanititiy of green electricity produced when $s^* = \underline{s}$ or $\overline{s}$ is so that a marginal change in the supply of either black or green electricity will not induce such a change from deficit to excess supply of green electricity, or vice verca.

$$p\left(x_M^*\right) = q_M^* + \alpha s_M^* \quad (5)$$
$$x_M^* = y_M^* + z_M^* < \frac{z_M^*}{\alpha}, \text{ or } x_M^* = y_M^* + z_M^* = \frac{z_M^*}{\alpha}, \text{ or } x_M^* = y_M^* + z_M^* > \frac{z_M^*}{\alpha} \quad (6)$$
$$\frac{\partial p(x_M^*)}{\partial x} x_M^* + q_M^* + s_M^* = h'\left(z_M^*\right) \quad (7)$$
$$\frac{\partial p(x_M^*)}{\partial x} x_M^* + q_M^* = c'\left(y_M^*\right) \quad (8)$$

The following proposition states that an equilibrium TGC price may be established at an intermediate level between the price limits when a single producer generates both green and black electricity. It also states that the effects of a change in the percentage requirement on electricity generation, in general, are all indeterminate under monopoly.

Proposition 2 *Assume that a monopolist generates both green and black electricity, then - in equilibrium - the TGC price may be established at i) an intermediate level, i.e.* $\underline{s} < s_M^* < \overline{s}$ *or at ii) either of the price bounds, i.e.* $s_M^* = \underline{s}$ *or* $s_M^* = \overline{s}$. *Furthermore, iii) the effects of a change in the percentage requirement,* α, *on total electricity consumption* x_M^*, *green electricity generation* z_M^*, *and black electricity generation,* y_M^* *are generally indeterminate, but equal to the effects under perfect competition if* $\left((dp(x_M^*)/dx) + \left(d^2p/dx^2\right) x_M^*\right) < 0$ *(thus covering the case of a linear demand function).*

Proof. *See appendix A and B.* ■

The reason why the existence of an intermediate TGC price under monopoly is stressed, is that it runs counter to the cases where the producers possessing market power are specialized in either green or black electricity generation. This is considered in the next main section.

5 Stackelberg game with interactive electricity and TGC markets

In this section we consider the case of market power in the TGC market. Such a case may arise if one producer (or a few producers) has exclusive access to particularly good sites for green electricity generation (e.g. water power, or wind power).[13] As the producer of green electricity is also the only supplier of TGCs, the producer, thus, possesses market power in the TGC market. We consider a case where the green producer only generates green electricity and not black electricity, while the producer of black electricity only generates black electricity and not green electricity. As for the generation of black electricity one may for instance consider the case of a competitive fringe, a Nash-Cournot (NC) oligopoly, or a Stackelberg leadership model. The objective of this paper is to investigate the effects of market power exertion, and in particular a setting where also a producer of black electricity recognizes that his actions in the electricity market have an effect in the TGC market. As this is the objective it seems reasonable to assume that the producer of black electricity also recognizes that he can influence the green producer's decisions in the electricity market. In accordance with this we shall therefore consider a Stackelberg game. We, thus, consider a standard Stackelberg model, where the producer of black electricity is the leader and the producer of green electricity is the follower.

Hence, in the following we take the interaction between the TGC market and the electricity market into account i.e. we assume that the producers may take account of the effects on both markets of decisions made in the electricity market. The producer of green electricity is assumed to recognize that a reduction of green electricity also implies a reduction of the number

[13] An example of this could be Dong Energy in the Jutland-Fuen price areathat has an exclusive access to the wind power sites in the Nord Pool market.

of TGCs issued and consequently that both markets may be affected by the reduction of green electricity generated. Likewise, a producer of black electricity possessing market power is assumed to recognize that a reduction of black electricity generation will affect both the electricity market as well as the TGC market through the percentage linkage of demand.[14].

We start by considering the optimal behaviour of the green producer acting as a follower. In accordance with standard assumptions we assume that the green producer follows a Nash-Cournot (NC)-strategy and maximizes profit while considering the quantity of black electricity as given. Hence, for the moment supressing the subscript indicating market form, the green producer is assumed to maximize the following objective function, with y as a given:

$$\Pi\left(z,y\right)=q(z,y)z+s(z,y)z-h\left(z\right).$$

The first order condition of this maximization problem is equal to:

$$\frac{\partial\Pi}{\partial z}=\frac{\partial\left(q+s\right)}{\partial z}z+q+s-h^{'}\left(z\right)=0.$$

or, as $p(z+y)=q(z,y)+\alpha s(z,y)$:

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

The first order condition, implicitely defines a reaction function $z=R(y)$ for the producer of green electricity.

Next, we consider the producer of black electricity acting as a Stackelberg leader. In accordance with standard assumptions we assume that the leader maximizes profit taking the reaction function of the follower, $R(y)$, as given. In doing this the leader will also consider the effects of his quantity decision on the TGC price, because theTGC-price affects the wholesale price of electricity through the relation: $q(z,y)=p(z+y)-\alpha s(z,y)$. Thus, the producer of black electricity is assumed to maximize the following objective function :

$$\Pi\left(y,R(y)\right)=q\left(R(y),y\right)y-c\left(y\right).$$

The first order condition of this maximization problem is equal to:

$$\frac{\partial\Pi}{\partial y}=\left[\frac{\partial q}{\partial z}\frac{dR}{dy}+\frac{\partial q}{\partial y}\right]y+q-c^{'}\left(y\right)=0.$$

or equivalently:

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

As stated earlier, a marginal change in the generation of electricity, both black and green, may affect the wholesale price through both the electricity market and the TGC market. The

[14] This is different from a standard Cournot setting where the TGC price would have been treated as exogenous by both the producers of black and green electricity, i.e. neither of the producrs would realize that their quantity decisions in the electricity market would affect the TGC price and thereby the resulting wholesale price of electricity through the interaction between the electricity and the certificate market.

effect through the electricity market stems from an ordinary effect on the consumer price, while the effect through the TGC market stems from a change induced by the demand/supply of TGCs. Hence, 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, thus giving an upward pressure on the TGC price. Correspondingly, an increase in the generation of green electricity by one unit delivered to the market will also increase the consumption of electricity by one unit, and increase the demand for TGCs by α units, but also increase the number of TGCs by one unit. As, the increase of TGC demand is only a fraction α of the increase of TGC supply, the net effect is a downward pressure on the TGC price. Otherwise, it is important to stress that the demand for TGCs is a derived demand equal to a given percentage of the demand for electricity i.e. a fixed linkage meaning that the two demand functions are not independent.

5.1 Equilibrium under the Stackelberg game

The subscript S is used to identify the case of market power in interactive electricity and power markets. We then have the following equilibrium conditions (key variables denoted by a $*$):[15]

$$p\left(x_S^*\right) = q_S^* + \alpha s_S^* \tag{9}$$

$$x_S^* = y_S^* + z_S^* < \frac{z_S^*}{\alpha}, \text{ or } x_S^* = y_S^* + z_S^* = \frac{z_S^*}{\alpha}, \text{ or } x_S^* = y_S^* + z_S^* > \frac{z_S^*}{\alpha} \tag{10}$$

$$\left[\frac{\partial p(x_S^*)}{\partial x} + (1-\alpha)\frac{\partial s(z_S^*, y_S^*)}{\partial z}\right] z_S^* + q_S^* + s_S^* = h^{'}\left(z_S^*\right) \tag{11}$$

$$[\frac{\partial p(x_S^*)}{\partial x}(\frac{dR}{dy}+1) - \alpha(\frac{\partial s(z_S^*, y_S^*)}{\partial z}\frac{dR}{dy} + \frac{\partial s(z_S^*, y_S^*)}{\partial y})]y_S^* + q_S^* = c^{'}\left(y_S^*\right) \tag{12}$$

The possibility of affecting the TGC price depends, however, on whether the TGC price is either at the upper or lower price bound or between the upper and lower price bounds. If the TGC price is at either of the price bounds, the effect on the TGC price of a marginal change of the generation of black or green electricity (i.e. $(\partial s/\partial y)$ or $(\partial s/\partial z)$) is equal to zero, just as for a pure monopoly.[16] In these cases the wholesale price can only be affected through the electricity market (i.e., the ordinary price effect). If, however, the TGC-price were between the price bounds, the producers could also influence the wholesale price through the TGC market. For this case, the marginal effect on the TGC price (i.e. $(\partial s/\partial y)$ or $(\partial s/\partial z)$) would not be defined as the marginal revenue is discontinuous at this point. Accordingly, the producer of black electricity can induce a reduction of demand for TGCs and thus create an excess supply of TGCs by marginally reducing the generation of black electricity. The consequence of this is a drop of the TGC price to its lower bound and a corresponding upward jump of the wholesale price. The composition of the end user electricity price is thus changed to the benefit of the producer of black electricity. Likewise the producer of green electricity may use the market power to reduce the generation of green electricity and TGCs marginally and thus create an excess demand for TGCs. This leads to a jump of the TGC price to its upper bound and a corresponding reduction of the wholesale price.

The possibility of creating price jumps in the TGC market (due to the fixed linkage with the electricity market) implies that the green producer (the last mover) always has the option of profitably generating an upward jump of the TGC price, if an intermediate TGC price should

[15] For the cases of $s_S^* = \underline{s}$ and $s_S^* = \overline{s}$, we have $\left(\partial s\left(x_S^*\right)/\partial z\right) = \left(\partial s\left(x_S^*\right)/\partial y\right) = 0$. Thus, (11) and (12) are reduced to $\left(\partial p\left(x_S^*\right)/\partial x\right) z_S^* + q_S^* + s_S^* = h^{'}\left(z_S^*\right)$ and $\left(\partial p\left(x_S^*\right)/\partial x\right)((dR/dy)+1)y_S^* + q_S^* = c^{'}\left(y_S^*\right)$, respectively.

[16] See footnote 12.

emerge as a result of the quantity decision made by the Stackelberg leader. Hence, an intermediate TGC price can not be an equilibrium price. This does not mean, however, that the equilibrium TGC price is always at the upper price bound. The optimal quantity response of the green producer may well result in an equilibrium TGC price at the lower price bound. This is foreseen by the Stackelberg leader through the knowledge of the reaction function of the follower. Hence, these relationships imply that the TGC market collapses in the sense that the TGC price will never be established at an intermediate level. These results are stated in Proposition 3.[17]

Proposition 3 *Assume that the producer of black electricity acts as a Stackelberg leader and the producer of green electricity acts as an NC-playing follower in interactive electricity and TGC markets, then - in equilibrium - the TGC-price will equal either the lower or the upper price bound and never lie within the two bounds, i.e.* $s_S^* = \underline{s}$ *or* $s_S^* = \overline{s}$.

Proof. *See appendix A and B.* ■

5.2 Illustrations

Fig.1. and Fig. 2. illustrate the profit curves of the the producer of green electricity under a setting of Stackelberg leadership. The figures are based on a simple numerical model satisfying the assumptions of the model, see Appendix B. The profit curve of the green producer (the follower) is generated assuming that the quantity of black electricity is fixed at the profit maximizing level of the producer of black electricity (the leader). The producer of green electricity generates an amount correspondig to the maximum profit, as foreseen by the producer of black electricity. These solutions maximize the profits of the producer of black electricity. Fig. 1. shows an equilibrium at the upper TGC price bound, while Fig. 2 shows an equilibrium at the lower TGC price bound.

[17] The results of assuming that the producers of black electricity behave like a competitive fringe, or a NC-oligopoly, while the producers of green electricity behave like a NC-playing group are easily deductible from the the analysis of Stackelberg model. In fact all cases give the same result i.e. the TGC price will always be established at either the upper or the lower price bound. Proofs may be obtained from the authors upon request.

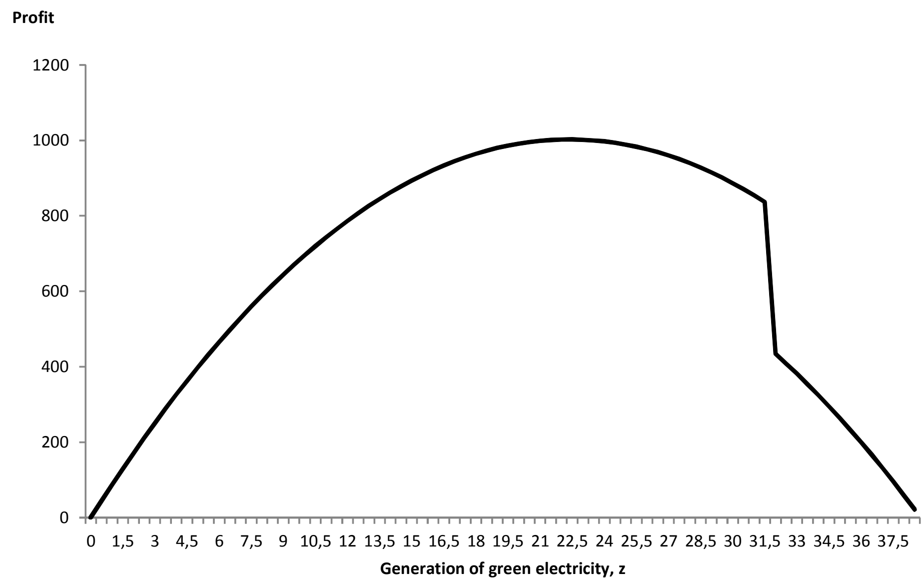

Fig. 1. Profit of green electricity generation. Stackelberg equilibrium at upper TGC price.

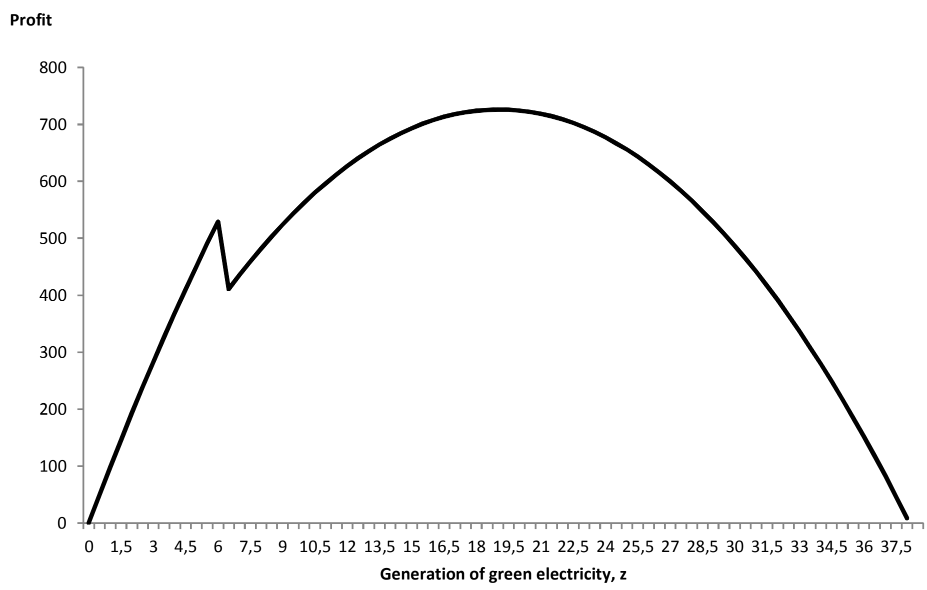

Fig. 2. Profit of green electricity generation. Stackelberg equilibrium at lower TGC price.

In particular, we observe the discontinuity of the profit curves. Looking first at Fig.1. we note that the profit of the producer of green electricity drops (discontinuously) at a specific value of z. This is the quantity of green electricity at which total consumption of electricity is at the allowable consumption level (i.e. $z = \alpha x$). At this quantity level the TGC price jumps from the upper TGC price bound to the lower TGC price bound, resulting in a drop of profit. At lower production levels of green electricity, there is an excess demand of TGCs, i.e., the TGC price is at the upper TGC price bound. For higher production levels of green electricity, there is an excess supply of TGCs wherefore the TGC price is at the lower bound. The case illustrates that the producer of black electricity does not necessarily induce a TGC price at the lower bound.

Fig. 2. again illustrates the profit curve of the green producer for increasing generation levels of green electricity as the production of black electricity is fixed at the optimal level for the producer of black electricity. This case has a lower percentage requirement, but is otherwise equal to the case of Fig. 1. Again, the drop of profit takes place at a production level of green electricity for which $z = \alpha x$. At this point the TGC price drops from its upper bound to its lower bound. For higher production levels the profits starts to rise again and reaches a maximum at the level corresponding to the Stackelberg equilibrium.

6 Summary and concluding remarks

This paper examines how an electricity market and a Tradable Green Certificates (TGC) market function when it is recognized that such markets are strongly interlinked and the producers of electricity (green and black) take the interlinkage into account in their production decisions. The results of the paper are summarized in Propositions 1-3.

An essential element of a TGC system is that the number of TGCs issued functions as a check on total electricity consumption, in that the total amount of electricity consumed requires the possession of an amount of TGCs corresponding to a given percentage of the electricity consumption. Hence, total electricity consumption can be no larger than the number of TGCs sold divided by the percentage requirement (unless the TGC price tends to rise above a certain upper price bound as set by the regulatory authority).

The direct linkage between the two markets implies that a marginal change in the generation of electricity not only influences the price in the electricity market directly, but also indirectly through the effect on the TGC price. Recognizing this, the paper considers a setting of interactive functioning markets that goes beyond a traditional analysis of a producer operating in two markets where the producer considers the price of the other market as given, when deciding how much to produce in one of the markets. Potentially, this may give rise to problems with respect to the functioning of the markets. However, the paper shows that no such problems arise under perfect competition as the producers take the prices as given anyway. Furthermore, and perhaps more interestingly, the same is the case under a pure monopoly, where the producer generates both green and black electricity[18]. Hence, for this case the effect of market power on market prices and quantities are shown to be as expected using standard economic models.

However, a problem arises when there is a combination of market power and a specialization of production, i.e. when some producers only produce green electricity and others only produce black electricity. The specialization implies that the producers may have differing benefits of a high or a low TGC price. By taking the interaction between the two markets into consideration, the

[18] The same would also be true for an oligopoly of identical producers, generating both green and black electricity.

results are altered as compared with the results that would emerge using standard Nash Cournot assumptions under market power for the two markets, see Amundsen and Bergman (2012). In particular, the paper shows that market power will prevent the realization of a market-based TGC price within the specified price interval, i.e. the TGC price will either be established at the upper or the lower price bound. Thus, the TGC system will reduce to a system corresponding to direct subsidies financed through consumer/producer taxes. The paper shows this result for the case of Stackelberg leadership where the producer of black electricity acts as a leader and the producer of green electricity acts as a Nash Cournot playing follower. However, the validity of this result does not limit itself to the Stackelberg setting, but will be equally valid if black electricity were produced by a competitive fringe or by Nash Cournot playing oligopolists.The important feature is that a specialized producer with market power always can make the TGC price jump in a preferred direction by quantity adjustments in the electricity market.

In view of this result, the TGC price bounds will play an instrumental role in the subsidization of green electricity generation when the conditions mentioned above are full filled. In general, the basic rationale for adding price bounds in the TGC system is similar to the rationale of combining price bounds with a system of tradable permits in regulating the emission of a pollutant. For the latter case it has been shown that the combination of systems minimizes the expected loss of fixing either an in-optimal level of a Pigouvian tax or issuing an in-optimal amount of permits in the face of missing information with respect to the true position of the marginal abatement cost curves, see e.g. Weitzman, 1974 and Roberts and Spence (1976). Hence, under perfect competition or a pure monopoly the price bounds in the TGC system are warranted. However, if the conditions are such that the TGC system reduces to a system where either the upper or lower price bound is established, it would seem more natural to replace the system by a single unit subsidy of green electricity generation. This will also eliminate market power exertion, as the producers can not influence the size of the subsidy. Alternatively, regulating authorities could issue a tender for a given amount of green electricity. For the case of a fixed unit subsidy, uncertainty will pop up in terms of uncertain quantity of green electricity generated (while the subsidy is fixed). For the case of a tender, uncertainty will pop up in terms of the size of the subsidy (while the quantity is fixed).

While the non-existence of intermediate TGC prices in the face of market power is a clear cut result, it will not necessarily emerge in existing (or planned) TGC markets. Several conditions must be satisfied for this to be the case: possibility of exercising market power, producers separated into specialized production (either green or black electricity), and electricity and TGC markets that are simultaneously sensitive to price changes facing the end users of electricity. Considering the Norwegian-Swedish TGC market, the possibility of exercising market power is very low due to a large number of producers of both kinds of electricity. Furthermore, most producers of electricity are not specialized but have interests in the generation of both green and black electricity. Also, the retailing companies typically do not immediately pass on the TGC price to end users, but rather charge a fixed fee per unit electricity consumed to cover the purchase of TGCs at the end of the accounting period. Hence, from the point of view of end users it is as if the TGC price is fixed anyway. In this respect it does not deviate significantly from a standard tax on electricity consumption.

Even though several conditions must be full filled to have the claimed result of non existence of intermediate TGC prices, it is not the same as saying that such conditions never will be full filled. Generally, many electricity companies have considerable market power in their relevant markets e.g. the Danish company Dong in the Jutland price area of Nord Pool or, indeed, the many so called national champions like EDF. Furthermore, new large specialized producers of green electricity are entering the scene and may have an interest in keeping a high TGC price e.g. Statoil has no fossil generation of electricity but ventures into offshore wind power generation. Hence, in considering the introduction of a TGC system, one may be well advised to reconsider the simpler system of a feed in tariff. The TGC system may boil down to a fixed remuneration to green power generation anyway and to a presumable much higher cost to society of running an auction and controlling system for TGCs. Put differently, it is unlikely that it will be cost efficient to introduce a TGC system that ultimately functions like an ordinary subsidy scheme.

Another problematic feature of the TGC system, also shown in this paper, is that the percentage requirement in itself is not a precise 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 from 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 TGCs based on wind power) the problems revealed in this paper clearly call for caution in the design and implementation of TGC systems.

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Appendix A

A Proof of Proposition 1

Proof. *i)* For $\underline{s} < s_c^* < \overline{s}$, *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.* $p(x_c^*) = (1-\alpha)c'(y_c^*) + \alpha h'(z_c^*)$. *Take the implicit derivatives of this expression with respect to* α *and arrive at:* $(dz_c^*/d\alpha) = \left(\alpha s_c^* + x_c^*\left[(\partial p/\partial x) - (1-\alpha)c''(y_c^*)\right]\right)/D$, $(dy_c^*/d\alpha) = \left((1-\alpha)s_c^* + x_c^*\left[\alpha h''(z_c^*) - (\partial p/\partial x)\right]\right)/D$, *and* $(dx_c^*/d\alpha) = \left(s_c^* + x_c^*\left[\alpha h''(z_c^*) - (1-\alpha)c''(y_c^*)\right]\right)/D$, *with* $D = \left[(\partial p/\partial x) - (1-\alpha)^2 c''(y_c^*) - \alpha^2 h''(z_c^*)\right] < 0$. *Inspection of signs verifies the claims of the proposition.*

ii) For $s_c^* = \underline{s}$ or $s_c^* = \overline{s}$, *insert* (4) *in* (3). *Take the implicit derivative with respect to* α *and get* $h''(z_c^*)(dz_c^*/d\alpha) = c''(y_c^*)(dy_c^*/d\alpha)$. *As marginal costs are assumed increasing it follows:* $sign(dz_c^*/d\alpha) = sign(dy_c^*/d\alpha) = sign(dx_c^*/d\alpha)$. *The last equality follows as* $(dx_c^*/d\alpha) = (dz_c^*/d\alpha) + (dy_c^*/d\alpha)$. *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* $(\partial p/\partial x)(dx_c^*/d\alpha) = c''(y_c^*)(dy_c^*/d\alpha) + \widetilde{s}$, *where* $\widetilde{s} = \overline{s}$ *or* $\underline{s}$. *As* $(\partial p/\partial x) < 0$ *we must have* $(dx_c^*/d\alpha) < 0$ *for this equation to hold. Hence,* $sign(dz_c^*/d\alpha) = sign(dy_c^*/d\alpha) = sign(dx_c^*/d\alpha) < 0$ *for this case.* ■

B Proof of Proposition 2

Proof. *i) To show that there may be an interior TGC price,* $\underline{s} < s_M^* < \overline{s}$, *it suffices to give an example. This is provided in appendix B. The essential reason for the existence of such interior prices is that the monopolist is indifferent with respect to securing the high, the low or some intermediate TGC price (and correspondingly for the wholesale price) for the case where the optimal solution satisfies* $\hat{x} = \hat{y} + \hat{z} = (\hat{z}/\alpha)$. *To see this, consider the profit function for the monopolist* $\Pi(\hat{z}, \hat{y}) = q\hat{x} + s\hat{z} - c(\hat{y}) - h(\hat{z})$. *This may be rewritten:* $\Pi(\hat{z}, \hat{y}) = p\hat{x} + (\hat{z} - \alpha\hat{x})s - c(\hat{y}) - h(\hat{z})$. *However, as* $\hat{x} = (\hat{z}/\alpha)$ *the profit function reduces to* $\Pi(\hat{z}, \hat{y}) = p\hat{x} - c(\hat{y}) - h(\hat{z})$. *Hence, the value of* s *does not matter. Intuitively, a larger TGC price is exactly offset by a smaller wholesale price for this case. ii) To show that there may be a TGC-price at either the upper or the lower price bound, it suffices to give examples satisfying the assumptions of the model. See appendix B. iii)* For $\underline{s} < s_c^* < \overline{s}$, *inserting* (7) *and* (8) *into* (5) *yields the marginal revenue as a linear combination of marginal costs of the two groups of generation technologies in equilibrium, i.e.* $p(x_M^*) + (dp/dx)x_M^* = (1-\alpha)c'(y_M^*) + \alpha h'(z_M^*)$. *Take the implicit derivatives of this expression with respect to* α *and arrive at:* $(dz_M^*/d\alpha) = \left(\alpha s_M^* + x_M^*\left[(\partial p/\partial x) + (\partial^2 p/\partial x^2)x_M^* - (1-\alpha)c''(y_M^*)\right]\right)/D$, $(dy_M^*/d\alpha) = \left((1-\alpha)s_M^* + x_M^*\left[\alpha h''(z_M^*) - \right.\right.$ *and*$(dx_M^*/d\alpha) = \left(s_M^* + x_M^*\left[\alpha h''(z_M^*) - (1-\alpha)c''(y_M^*)\right]\right)/D$, *with* $D = \left[2(\partial p/\partial x) + (d^2p/dx^2)x_M^* - (1-\right.$
Inspection of signs verifies the claims of the proposition. However, if $(\partial p/\partial x) + (d^2p/dx^2)x_M^* < 0$, (that covers the case of linear demand), the signs are as in the competitive case. *For* $s_M^* = \underline{s}$ or $s_M^* = \overline{s}$, *insert* (8) *in* (7). *Take the implicit derivative with respect to* α *and get* $h''(z_M^*)(dz_M^*/d\alpha) = c''(y_M^*)(dy_M^*/d\alpha)$. *As marginal costs are assumed increasing it follows that:* $sign(dz_M^*/d\alpha) = sign(dy_M^*/d\alpha) = sign(dx_M^*/d\alpha)$. *The last equality follows as* $(dx_M^*/d\alpha) = (dz_M^*/d\alpha) + (dy_M^*/d\alpha)$. *To verify the signs insert* (8) *into* (5) *and take the implicit derivative*

with respect to α to obtain $((\partial p/\partial x)+\left(d^2p/dx^2\right)x_M^*)\,(dx_M^*/d\alpha)=c''\,(y_M^*)\,(dy_M^*/d\alpha)+\widetilde{s}$*, where* $\widetilde{s}=\overline{s}$ *or* $\underline{s}$*. If* $(\partial p/\partial x)+\left(d^2p/dx^2\right)x_M^*<0$ *we must have* $\left(dx_c^M/d\alpha\right)<0$ *for this equation to hold. Hence,* $sign\,(dz_M^*/d\alpha)=sign\,(dy_M^*/d\alpha)=sign\,(dx_M^*/d\alpha)<0$ *for this case (that covers the case of linear demand). If, however* $(\partial p/\partial x)+\left(d^2p/dx^2\right)x_M^*>0$,signs are generally indeterminate. ■

C Proof of Proposition 3

Proof. *i) Consider the quantity decision of the producer of green electricity (the follower). To show that we cannot have* $\underline{s}<s_m^*<\overline{s}$*, assume* $\hat{z}$ *is a solution satisfying the first order conditions for the producers of green electricity and that* $\overline{y}+\hat{z}=(\hat{z}/\alpha)$,which is a necessary condition for an intermediate TGC price. The symbol $\overline{y}$ denotes the quantity decision made by the producer of black electricity (the leader). *Clearly, if* $z<\hat{z}$*, then* $s_S^*=\overline{s}$*, due to excess demand of TGCs (i.e.* $z<\alpha\,(\overline{y}+z)$*) and if* $z>\hat{z}$*, then* $s_S^*=\underline{s}$*, due to excess supply of TGCs. The total revenue function of the green producer is equal to* $(q+s)z$ *and the marginal revenue function is equal to* $g\,(z,\overline{y})=((\partial\,(q+s)\,/\partial z))\,z+q+s$*. Observe that* $g\,(z,\overline{y})=(\partial p/\partial x)\,z+q+s$ *for* $z\neq\hat{z}$ *as* $(\partial s/\partial y)=0$ *for such values. Clearly,* $g\,(z,\overline{y})$ *is discontinuous at* $\hat{z}$ *as* $\lim\limits_{z\to\hat{z}^-}g\,(z,\overline{y})=(\partial p/\partial x)\,\hat{z}+\hat{q}^-+\overline{s}$ *and* $\lim\limits_{z\to\hat{z}^+}g\,(z,\overline{y})=(\partial p/\partial x)\,\hat{z}+\hat{q}^++\underline{s}$ *where* $\hat{q}^-=\lim\limits_{z\hat{\to}z^-}q=p\,(\overline{y}+\hat{z})-\alpha\overline{s}$ *and* $\hat{q}^+=\lim\limits_{z\hat{\to}z^+}q=p\,(\overline{y}+\hat{z})-\alpha\underline{s}$*. Inserting these expressions into the profit function* $\Pi\,(\hat{z},\overline{y})=(q+s)\,\hat{z}-h\,(\hat{z})$*, we see that* $(p\,(\overline{y}+\hat{z})-\alpha\overline{s}+\overline{s})\hat{z}-h(\hat{z})>(p\,(\overline{y}+\hat{z})-\alpha\underline{s}+\underline{s})\hat{z}-h(\hat{z})$*.Hence, profit maximization will lead the producer of green electricity to secure* $\hat{q}^-$ *(by an infinitesimal quantity reduction of green electricity) implying the corner solution* $s_S^*=\overline{s}$*. ii)*.To show that the equilibrium TGC price may be at either of the price bounds, it suffices to give examples satisfying the assumptions of the model. See Appendix B, and Fig. 1 and Fig. 2. ■

Appendix B

In this appendix we present a simple numerical model satisfying the assumptions of the analytical model. The model is used to give examples of 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 the figures of the paper.

We assume the following functions:
The inverse demand function is given by:
$p\,(x)=a-bx$,where a and b are strictly positive constants, $a,b>0$.
This gives:
$p'\,(x)=-b<0$.
The cost function for black electricity is:
$c\,(y)=0,5y^2$, with $c'\,(y)=y>0$ and $c''\,(y)=1$
The cost function for green electricity is:
$h\,(z)=(k/2)\,z^2+gz$, where $k,g>0$, with $h'\,(z)=kz+g>0$ and $h''\,(z)=k$, where k and g are strictly positive constants, $k,g>0$
der these assumptions the optimal solutions of the various markets forms are as follows:

Perfect competition: $z_C^*=(a-\alpha s-(1+b)(g-s))\,/\,(b+bk+k)$,

$y_C^* = (k(a - \alpha s) + b(g - s))\,(b + bk + k)$.

Monopoly: $z_M^* = (a - \alpha s - (1 + 2b)(g - s))\,/(2b + 2bk + k)$,

$y_M^* = (k(a - \alpha s) + 2b(g - s))\,(2b + 2bk + k)$. Calculations show that maximum profit is attained at a TGC price equal to $s_M^* = 76,2$ when $\alpha = 0,65$, $a = 100$, $b = 1$, $k = 2$, $g = 5$, $\overline{s} = 80$, $\underline{s} = 50$.

This is seen to be an interior solution for the TGC price, and is, thus, in accordance with the claim of Proposition 2, that such solutions exist under monopoly. Furthermore, if $\alpha = 0,4$, $a = 100$, $b = 1$, $k = 2$, $g = 5$, $\overline{s} = 25$, $\underline{s} = 10$, maximum profit is attained at the lower bound of the TGC price, $s_M^* = \underline{s} = 10$. Also, if $\alpha = 0,6$, $a = 100$, $b = 1$, $k = 2$, $g = 5$, $\overline{s} = 25$, $\underline{s} = 100$, maximum profit is attained at the upper bound of the TGC price, $s_M^* = \overline{s} = 25$.

Stackelberg solution: $z_S^* = ((2 + b)(a - \alpha s) - (2 + 3b)(g - s))\,/((1 + b)(4b + 3k) - k)$, $y_S^* = (2\,[(b + k)(a - \alpha s) + b(g - s)])\,((1 + b)(4b + 3k) - k)$, with $R(y) = (a - \alpha s - 3(g - s) + 2y)\,/\,(4b + 3k)$.

Assuming $\alpha = 0,6$, $a = 100$, $b = 1$, $k = 2$, $g = 5$, $\overline{s} = 40$, $\underline{s} = 10$, calculations show that $z_S^* = 22,4$, $y_S^* = 21,4$, $x_S^* = 43,9$. Because $z_S^* < \alpha x_S^*$, we have $s_S^* = \overline{s} = 40$, i.e. the upper TGC price bound, as illustrated in Fig.1.

Assuming $\alpha = 0,2$, $a = 100$, $b = 1$, $k = 2$, $g = 5$, $\overline{s} = 40$, $\underline{s} = 10$, calculations show that $z_S^* = 25,0$, $y_S^* = 26,8$, $x_S^* = 51,8$.Because $z_S^* > \alpha x_S^*$, we have $s_S^* = \underline{s} = 10$, i.e. the lower TGC price bound, as illustrated in Fig. 2.

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