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An Electricity Trading System with Tradable Green Certificates and CO_2 Emission Allowances

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Abstract

Combinations of various policy instruments to deal with the threat of climate change are used throughout the world. The aim of this article is to investigate an electricity market with two different policy instruments, Tradable Green Certificates (TGCs) and CO_2 emission allowances (an Emission Trading System, ETS). We analyze both the short- and long-run effects of a domestic market and a market with trade. We find that increasing the TGC quota obligation will decrease the electricity produced using non-renewable sources as well as the long-run total production of electricity. For the electricity produced using renewable energy sources, an increase in the quota obligation leads to increased production in almost all cases, with assumptions based on historical data. The impacts of the ETS price on the electricity production are negative for all electricity production, which is surprising. This means that the combination of ETS and TGCs gives unexpected and unwanted results for the electricity production using renewable sources, since an increase in the ETS price leads to a decrease in this production.

Keywords: Climate change; Tradable green certificates; Emission allowances; Electricity.

JEL Classification: Q40; Q42; Q48.

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1 Introduction

Growing concerns about climate change have led to a variety of mechanisms for promoting electricity from renewable energy sources. A number of different policy instruments are used throughout the world, and as the global climate negotiations slowly move forward, this situation will continue. Policy instruments to support electricity from renewable energy sources (RES-E) can be designed to directly increase RES-E production or to indirectly promote RES-E as a substitute for fossil fuel-based production (i.e. to reduce carbon emissions). Examples of the latter are the European Union Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative (RGGI), active across ten U.S. states, and a CO_2 tax. Examples of policies directly promoting RES-E are feed-in tariffs (FiTs) and tradable green certificates (TGCs). Numerous countries have combinations of policy instruments that affect the electricity production, directly and indirectly. On top of this, some policy instruments are domestic and others are traded internationally. In Sweden, the electricity market is deregulated since 1996 and the trade in electricity takes place at Nord Pool, the marketplace for trades in electricity for Sweden, Norway, Finland and Denmark.[1] The EU ETS started in 2005,[2] as an extension to the Kyoto agreement, with the objective to reduce CO_2 emissions at the lowest possible cost. At present, the EU ETS consists of 30 European countries, including Sweden and Norway. In May 2003 the market for TGCs started in Sweden and it will be extended to include Norway in 2012. The objective of the TGC market is to increase the percentage of the total electricity production that relies on renewable energy sources, so-called green electricity. Electricity consumers are obliged to possess a number of TGCs in relation to their total electricity consumption, determined by the quota obligation set by the Swedish Government. The producers that use renewable energy sources are allocated TGCs, representing the supply of TGCs. In Sweden, the type of energy plants that entitles TGCs are wind power, solar, wave and geothermal energy as well as bio-fuels, peat[3] and hydropower[4]. These two policy instruments coexist in the Swedish and Norwegian electricity markets, where the TGC system is designed to increase the part of the total generated electricity that comes from renewable energy sources, whereas the ETS is designed to decrease CO_2 emissions.

Some recent research has focused on these different policy instruments, but with less attention to how well the supporting policies work together or whether they may work at cross purposes. Fischer and Preonas (2010) review the recent environmental economics literature on the effectiveness of RES-E policies and on interactions between them. Special attention is given to Fischer (2009), that demonstrates how the relative slopes of supply and demand curves determine the price incidence of portfolio standards, showing that assumptions about renewable energy sources are more important than those about non-renewable supplies. Early contributions to the area include Morthorst (2001) and Jensen and Skytte (2002). Morthorst analyzes the pricing mechanism of a TGC system

[1] Not all countries have been part of the market since 1996. Norway was the first member (since 1993), and then Finland joined in late 1997, western Denmark in July 1999 and eastern Denmark joined in October 2000.

[2] The first three years, 2005-2007, it was a trial period called Phase I.

[3] When burnt in combined heat and power production (CHP) plants.

[4] With restrictions in capacity.

and an ETS in relation to the value of the emissions reductions, while Jensen and Skytte find that a combination of a TGC system and an ETS results in a lower consumer price. Böhringer and Rosendahl (2010) show that introducing a policy instrument that promotes electricity from renewable energy sources, in a market under autarky, leads to production increases in the dirtiest technology using non-renewable energy sources. Unger and Ahlgren (2005) show that most TGC markets will favor cheap renewable technologies before expensive ones. This will not promote the inventions and development of new renewable technologies. In line with Unger and Ahlgren, Bergek and Jacobsson (2010) and Jacobsson et al. (2009) criticize the TGC system due to the ineffectiveness in driving technical change. Bye (2003) models a TGC market and Bye and Bruvoll (2008) extend his model to include other subsidies and taxes, yet neither of these studies takes the ETS market into account. Rathmann (2007) shows that German electricity prices are reduced due to an RES-E system implemented in the German electricity market with EU ETS, for the period 2005-2007. Amundsen and Nese (2009) investigate the analytics of a TGC system and find that the TGC system may be an imprecise instrument to regulate the generation of green electricity, and that combining TGC with ETS may yield outcomes contrary to the intended purpose. Even though our model is inspired by the model in Amundsen and Nese, the settings in the models differ, especially as regards how the ETS is treated. Our study gives more structure to the model and analyses short- and long-run effects. The earlier study by Amundsen and Mortensen (2001) preceding Amundsen and Nese investigates the relationship between the TGC and ETS markets by focusing on the Danish market. Thus, they assume a given capacity in the green electricity production, since in Denmark all green electricity production is wind power. Amundsen et al. (2006) use an intertemporal simulation model that allows for banking, and conclude that banking reduces the price of green certificates. Pethig and Wittlich (2009) find that if a country targets both emissions and renewable targets, mixed policies are preferred, provided that both policy instruments are binding, while Abrell and Wiegt (2008) find that with ETS and TGC or feed-in tariffs (FiTs), the price of carbon drops to zero due to the existing high share of CO_2-neutral renewable generation.

The above discussion on previous literature shows the great variety in the previous research. Moreover, the qualitative model results are to a large extent undetermined. We believe that the complexity of the policies is one reason for this. Thus to remove some of the question marks and obtain more clear results, it seems necessary to introduce stronger, but reasonable, assumptions imposing more structure on the TGC market models. Our study will analyze a country with an existing well-functioning electricity market with an emission trading system (ETS) and a TGC market. We will cover both a domestic TGC system and an extended TGC system with trade, both with a short-run and a long-run perspective. The distinction between short run and long run is of great importance since this makes it possible to introduce stronger assumptions about the shape of the marginal cost functions. The focus will be on the TGC market and its impact on the production using renewable versus the production using non-renewable energy sources. We will set up a model and perform an analytical discussion on the electricity production and the impacts of a TGC quota and the ETS price, distinguishing between short- and long-run effects. The simplifying but reasonable assumptions we make is that in the short run marginal cost in renewable electricity production is constant and zero (due to hydro and wind power), while in the long run the marginal cost in black electricity production is constant because of long-run constant returns to scale. We will also look into the empirical data, where needed. We believe that the short-run/long-run distinction is the key to obtain distinct results. Although we observe no differences for the time horizons in the actual results, it should be remembered that the underlying assumptions are different between the short- and the long-run. The paper is organized as follows. We will start with a model description and the general results in Section 2. Section 3 discusses the short-run assumptions used and presents the results for the short run analysis, and Section 4 does the same for the long run analysis. In Section 5 we take a closer look at the Nordic electricity market, and Section 6 discusses an extended TGC market. Section 7 concludes the paper, with the results and a discussion.

2 The general model

We will formulate a static model of an electricity market. We have two types of producers; black electricity producers, using non-renewable energy sources, and green electricity producers, using renewable energy sources. The following labels and functions will be used in the model:

Labels and functional relationships

y_b	black electricity, produced using non-renewable sources
y_g	green electricity, produced using renewable sources
y	total production of electricity, $y = y_b + y_g$
$p(y)$	price of electricity, with $\frac{\partial p}{\partial y} < 0$
p_{tgc}	price of green certificates
p_{ets}	price of emission allowances
α	quota obligation for green certificates, as a percentage of total electricity
γ	CO_2 emission density
$c_i(y_i)$	cost function for black/green electricity production
	with $\frac{\partial c_i}{\partial y_i} > 0$ and $\frac{\partial^2 c_i}{\partial y_i^2} \geq 0,$ for $i = b, g$

The number of TGCs is measured in the same unit as the amount of green electricity. The demand for TGCs is given by αy, since all producers are obliged to hold a number of TGCs equal to α times their production[5]. The supply is given by y_g, since this is the number of TGCs available in the market. This gives $y_g = \alpha y$. There will be producers that do not qualify as green electricity producers but have no CO_2 emissions; this is not a problem since they will be classified as black electricity producers with γ set to zero.[6] The model originates in the profit maximization problem for the producers. The maximization problem for the producer of black electricity is

$$\max py_b - c_b(y_b) - \alpha p_{tgc} y_b - \gamma p_{ets} y_b,$$

[5] In this model we assign the obligation to hold TGCs to the producers of electricity, while in reality the obligation is assigned to the suppliers/consumers of electricity. However, theoretically this does not make a difference and does not restrict the model.

[6] Unfortunally it is, in this setting, not possible to treat these producers separately.

giving the first-order conditions for an optimum

$$p = \frac{\partial c_b}{\partial y_b} + \alpha p_{tgc} + \gamma p_{ets}. \tag{1}$$

The maximization problem for the producer of green electricity is

$$\max p y_g - c_g(y_g) + (1-\alpha)\, p_{tgc} y_g$$

and the first-order conditions for an optimum is

$$p = \frac{\partial c_g}{\partial y_g} - (1-\alpha)\, p_{tgc}. \tag{2}$$

Solving equation (2) for p_{tgc} and inserting the expression for p_{tgc} in equation (1) gives

$$p = (1-\alpha)\frac{\partial c_b}{\partial y_b} + \alpha \frac{\partial c_g}{\partial y_g} + (1-\alpha)\,\gamma p_{ets}. \tag{3}$$

Impacts of the quota obligation

Implicitly differentiating equation (3) with respect to α, and using that $y = y_b + y_g$ and $y_g = \alpha y$, we get the impacts of the quota obligations on y_b, y_g and y:[7]

$$\frac{\partial y_b}{\partial \alpha} = \frac{\frac{1}{1-\alpha} y_b \left(\alpha \frac{\partial^2 c_g}{\partial y_g^2} - \frac{\partial p}{\partial y}\right) + \left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{4}$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{a} y_g \frac{\partial p}{\partial y} - \frac{(1-\alpha)}{a} y_g \frac{\partial^2 c_b}{\partial y_b^2} + \frac{a}{1-\alpha}\left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \tag{5}$$

$$\frac{\partial y}{\partial \alpha} = \frac{a y \frac{\partial^2 c_g}{\partial y_g^2} - y(1-\alpha)\frac{\partial^2 c_b}{\partial y_b^2} + \frac{1}{(1-\alpha)}\left(\frac{\partial c_g}{\partial y_g} - p\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}. \tag{6}$$

When looking at the impacts of the quota obligation, we see that the denominator is the same and negative for the impacts on both types of electricity production and the total production. The impact of the quota obligation on the black electricity is negative, since all included terms in the numerator are positive. This means that if the quota obligation, α, increases, then the production of black electricity decreases. The numerators are undetermined for green electricity and total consumption, so we need to take a closer look at the included terms, and in the following sections we study the two different time preferences, i.e. the short- and long-run aspects. But first we use the general model to reveal the impacts of the ETS price.

[7] The calculations are available on request

Impacts of the ETS price

Moving on to study the impact of the ETS price on electricity production, we take the implicit derivative with respect to p_{ets} in equation (3) and get the impacts of the price of ETS on y_b, y_g and y:

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2 \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \tag{7}$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha (1-\alpha) \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}, \tag{8}$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha) \left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2 \frac{\partial^2 c_b}{\partial y_b^2} - a^2 \frac{\partial^2 c_g}{\partial y_g^2}}. \tag{9}$$

We see that the signs of the impacts on the black, green and total production will always be the same and depend on the magnitude of γ (the CO_2 emission density) in relation to the sign and magnitude of $p_{ets}\frac{\partial \gamma}{\partial p_{ets}}$. We need to study the included terms in more detail, in the short- and long-run analyses, but let us first summarize the results for the general model in Table 1.

Table 1: Summary of the results for the general model.

	General model
$\frac{\partial y_b}{\partial \alpha}$	-
$\frac{\partial y_g}{\partial \alpha}$	?
$\frac{\partial y}{\partial \alpha}$	?
$\frac{\partial y_b}{\partial p_{ets}}$	?
$\frac{\partial y_g}{\partial p_{ets}}$	?
$\frac{\partial y}{\partial p_{ets}}$	?

The number of question marks in Table 1 illustrates the need for stronger assumptions to obtain clear results. The next section will discuss the assumptions for the short run and present the impacts of the quota obligation and the price of the ETS on electricity production. However, interesting conclusions can still be drawn at this stage. First, the only clear impact of the quota obligation is on the production of black electricity. This is a bit surprising since the purpose of the TGC system is to *promote green electricity* and not to decrease black electricity production, even if this is an expected outcome. Further we see that the impact of the ETS price will have the same sign for both types of electricity production and for the total electricity production, which is also a bit surprising. One might expect that the sign of the impacts on the production of green electricity and on the production of black electricity to differ. We will try to straighten out all question marks in Table 1, starting with the analysis of the short run. In the following we will make assumptions based on the Nordic market situation, however we believe that the assumptions are reasonable in other markets as well.

3 The model in the short run

In the short run we will assume that the marginal cost of green electricity production is constant, since the short run changes are made in existing hydro and wind power plants. Hence $\frac{\partial^2 c_g}{\partial y_g^2} = 0$. The cost function for black electricity, c_b, can be expressed as $c_b = y^b$, where $b \approx 1.2$.[8] Further, we assume that the demand for electricity can be written $y = Dp^\eta$, and hence $y\frac{\partial p}{\partial y} = \frac{1}{\eta}p$, where η is the price elasticity of demand for electricity. A price elasticity of -0.1 is used in both Bye (2003) for the Norwegian electricity market and De Jonhe et al. (2009) for the Benelux, France and Germany markets. Johnsen et al. (2000) presents a table of price elasticities for *residential* electricity demand, ranging from -0.19 to -0.76, based on empirical studies across the world. They find that, in Norway, the price elasticity can be estimated to -0.1 to -0.2. Based on this previous research, for the short run, we assume that $0.1 < |\eta| < 0.3$.

Impacts of the quota obligation

Using some of the assumptions described above, equation (5) can be rewritten as

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2} + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\, \frac{\partial^2 c_b}{\partial y_b^2}}. \tag{10}$$

The denominator is still negative and for the numerator we have $\frac{1}{\eta}p-(1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2} < 0$ and $\alpha p_{tgc} > 0$. Thus if $\left|\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2}\right| > \alpha p_{tgc}$, we have that $\frac{\partial y_g}{\partial \alpha} > 0$. To simplify the analysis we use $\left|\frac{1}{\eta}p - (1-\alpha)\, y\frac{\partial^2 c_b}{\partial y_b^2}\right| > \left|\frac{1}{\eta}p\right|$, and it is therefore enough to show that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ to state that $\frac{\partial y_g}{\partial \alpha} > 0$. The restriction for η,

[8] This assumption relates to the principal merit order curve in Swedish electricity production. See for instance www.svenskenergi.se

i.e. $0.1 < |\eta| < 0.3$, is equal to $10 > \left|\frac{1}{\eta}\right| > 3\frac{1}{3}$. Since by definition $0 < \alpha < 1$, we have that $\left|\frac{1}{\eta}\right| > \alpha$.[9] Therefore, to be able to show that the impact of the quota obligation is positive, it is enough to show that $p > p_{tgc}$. We believe that $p > p_{tgc}$ most of the time, yet we are unable to state this for certain. Hence, we are not able to determine the sign of the impact of the quota obligation on the green electricity production, since we need either $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ or $p > p_{tgc}$. However, to gain more insight into this matter, we study this case in Section 5, Visiting the Nordic Electricity market.

Rewriting the derivative for the total electricity, i.e. equation (6), using the short-run assumptions gives

$$\frac{\partial y}{\partial \alpha} = \frac{-y\,(1-\alpha)\,\frac{\partial^2 c_b}{\partial y_b^2} + p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\,\frac{\partial^2 c_b}{\partial y_b^2}} = \frac{-\,(1-\alpha)^{b-1}\,b(b-1)D^{b-1}p^{(b-1)\eta} + p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\,\frac{\partial^2 c_b}{\partial y_b^2}}. \quad (11)$$

Here we have the negative term $-\,(1-\alpha)^{b-1}\,b(b-1)D^{b-1}p^{(b-1)\eta}$ and the positive term αp_{tgc}. We see that the sign of $\frac{\partial y}{\partial \alpha}$ will depend both on the assumptions for the short run, i.e. b, D and η, and on the prices of electricity and TGCs. We know that $0.1 < |\eta| < 0.3$, $b \approx 1.2$ and $y = Dp^{\eta}$ (and therefore $D = \frac{y}{p^{\eta}}$). Unfortunately, we are unable to determine the sign of the impacts on the total electricity production since we need to know the relationship between p_{tgc}, p and y. This relationship will be analyzed Section 5.

Impacts of the ETS price

In the short run we assume that $\frac{\partial \gamma}{\partial p_{ets}} = 0$ since the producers have no possibility to react to a change in the ETS price by changing their CO_2 emission density. The equations (7), (8) and (9) can now be rewritten as

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\,\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\,\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0, \quad (12)$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha\,(1-\alpha)\,\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\,\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0, \quad (13)$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\,\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\,\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0. \quad (14)$$

The impact on all types of electricity production is negative, meaning that an increase in the price of the emission allowances gives rise to a decrease in the

[9] Actually, it is possible to put a harder restriction on α since the quota obligation for the green certificates ranges (for Sweden) from 0.1 to 0.2 from 2011 to 2028. After 2028, the quotas will decrease and go down to 0,008 in 2035, which is, at this point, the last year for the TGC system in Sweden. However, at this stage of the analysis we do not need a harder restriction than $0 < \alpha < 1$.

electricity production. As stated before, the signs are the same for all types of production and noteworthy, there is a negative impact of the price of the emission allowances on the green electricity production. This is not an expected result and shows that the combination of the ETS and TGC markets appears to work contradictorily with respect to the production of electricity using renewable sources. Increasing the price of the emission allowances works restrictively on the black electricity production (in line with the aim of the ETS), but also on the green electricity production. Further we see that the impact is larger on the black electricity production than on the green electricity production.[10] In the next section we will study the long run impacts.

4 The model in the long run

In this section we move the focus to a long-run static equilibrium. We do not take investments or other capacity changes into account. Further, the cost functions in the long run are not the same as the cost functions in the short run, yet for simplicity, we have the same notations as in the short run. In the long run, we assume that the marginal cost of the black electricity is constant, so $\frac{\partial^2 c_b}{\partial y_b^2} = 0$, due to long-run constant returns to scale. Further, we still assume that the demand for electricity can be written $y = Dp^\eta$, but with η less than -0.3.

Impacts of the quota obligation

Using these assumptions, equation (5) can be rewritten as

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}}. \tag{15}$$

Again we need a more careful study of the included terms. We study the numerator of $\frac{\partial y_g}{\partial \alpha}$, where $\frac{1}{\eta}p < 0$ and $\alpha p_{tgc} > 0$. Either we stop here and say that if $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ we have a positive impact of the quota obligation on the green electricity production or we try to split up the terms. We know that $|\eta| > 0.3$ and to get $\left|\frac{1}{\eta}\right| > \alpha$ we need to put a restriction on α. If we assume that $\alpha < 0.5$ then $|\eta| < 2$.[11] Following the discussion for the short run we therefore either need $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ or $p > p_{tgc}$ to state that the impact on the green electricity production is positive. Again we cannot determine the sign of the impact of the quota obligation on the green electricity production without further assumptions on p and p_{tgc} (see Section 5). For total electricity we have

[10] As long as α is smaller than 0.5.

[11] $|\eta| = 2 \Leftrightarrow \left|\frac{1}{\eta}\right| = 0.5$. As mentioned ealier, an $\alpha < 0.5$ is a reasonable assumption. In Sweden α ranges from 0.1 and 0.2 from 2011 to 2028. An upper limit of $|\eta| = 2$ is reasonable and we do not believe that the long-term price elasticity of electricity will be nearly as high as 2. See for instance Dahl (1993) for a literature review on price elasticities.

$$\frac{\partial y}{\partial \alpha} = \frac{\alpha y \frac{\partial^2 c_g}{\partial y_g^2} + p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2 \frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{16}$$

since the numerator is positive, meaning that an increased quota obligation gives rise to a decrease in the total electricity production. This is an expected result and together with the negative impact on the black electricity production we can state that the impact on the green electricity production has to be larger than the impact on the black electricity production ($\frac{\partial y_g}{\partial \alpha} > \frac{\partial y_b}{\partial \alpha}$). This can be fulfilled with $\frac{\partial y_g}{\partial \alpha} > 0$ or $\frac{\partial y_g}{\partial \alpha} < 0$, but in the latter case we also need $\left|\frac{\partial y_g}{\partial \alpha}\right| < \left|\frac{\partial y_b}{\partial \alpha}\right|$. The expected result would of course be $\frac{\partial y_g}{\partial \alpha} > 0$, but if $\frac{\partial y_g}{\partial \alpha} < 0$, the decrease in the green electricity production would be less than the decrease in the black electricity production.

Impacts of the ETS price

In the long run, firms can shift their production towards technologies with lower emission density which means that $\frac{\partial \gamma}{\partial p_{ets}} < 0$ rather than $\frac{\partial \gamma}{\partial p_{ets}} = 0$. Further we believe that the price elasticity for CO_2 emissions is inelastic, since the ETS price has a relatively small effect on the quantity of CO_2 emissions. An inelastic price elasticity means that $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} > -1$. Hence the impacts of the ETS price in the long run will be written,

$$\frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{17}$$

$$\frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0, \tag{18}$$

$$\frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0. \tag{19}$$

The sign of the equations (17), (18) and (19) will depend on the mutual relationship between γ and $p_{ets}\frac{\partial \gamma}{\partial p_{ets}}$. The breakeven point, where the impacts of the ETS price change sign, is where $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} = -1$, meaning that the breakeven point is where the price elasticity for CO_2 emissions equals -1. Therefore, since we assume that the demand for CO_2 emissions is inelastic,[12] we will have a negative impact of the ETS price on both types of electricity production and on the total electricity production.[13] Further we see that the impact is larger on the

[12] $\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} > -1$

[13] However, if the price elasticity for CO_2 emissions is elastic $\left(\frac{p_{ets}}{\gamma}\frac{\partial \gamma}{\partial p_{ets}} < -1\right)$, we will have a positive impact of the ETS price on both types of electricity production and on total electricity production. We believe this to be highly unlikely.

black electricity production compared to the green production.[14] However, we still have the obscure result for the impact on the green electricity production (see the discussion in the short run and in the concluding section).

5 Visiting the Nordic Electricity Market

In order to shed some more light on the undetermined signs of the impacts of the quota obligation on electricity production, we take a closer look at the available data. We use historical time series for Sweden for the price of electricity and TGCs and for the amount of electricity produced. The undetermined impacts and the relationships we want to understand, are:

- the impacts of the quota obligation on the green electricity production (both short and long run): $\frac{1}{\eta}p$ in relation to αp_{tgc}
- the impacts of the quota obligation on the total electricity production in the short run: $-(1-\alpha)^{b-1} b(b-1)D^{b-1}p^{0,2\eta}$ in relations to αp_{tgc}.

Impacts of the quota obligation on the green electricity production

We start with the impacts on the green electricity production, and as stated above we need to know the relation between $\frac{1}{\eta}p$ and αp_{tgc}. We know that $\frac{\partial y_g}{\partial \alpha} > 0$ if $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$, both for the short and long run. The price of electricity, p, is the price before the TGCs, emission allowances and taxes, and can be interpreted as the system price of electricity at Nord Pool, while p_{tgc} is the price of the green certificates. We study the historical time series for the prices 2004-2010 (Nord Pool Spot 2011; Svenska Kraftnät[15] 2011) and see that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ for every day during this period, with $0.1 < |\eta| < 0.3$.[16] For the long run we have $|\eta| > 0.3$, and with $|\eta| < 2$ we have that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ also in the long run[17]. Therefore, based on the empirics from 2004–2010, we state that the impacts of the quota obligation on the green electricity production are positive, both in the short and long run.

Impacts of the quota obligation on the total electricity production, short run

We use time series for 2008-2010 from Nord Pool Spot(2011) for the electricity price and from Svenska Kraftnät (2011) for electricity production to determine the size of D and the prices. We see that for $0.1 < |\eta| < 0.3$ together with $1.1 < b < 1.3$, $\frac{\partial y}{\partial \alpha} < 0$, but if b exceeds 1.3 there is a shift in the sign and

[14] As long as α is smaller than 0.5.

[15] The Swedish national grid.

[16] With $\alpha = 0,081$ (2004), $\alpha = 0,104$ (2005), $\alpha = 0{,}126$ (2006), $\alpha = 0,151$ (2007), $\alpha = 0,163$ (2008), $\alpha = 0,17$ (2009) and $\alpha = 0,179$ (2010). Actually $p > p_{tgc}$ for almost all dates, except for a small number of days, (less than 25 days a year) where $p < p_{tgc}$. However since $\left|\frac{1}{\eta}\right| > \alpha$ for these days still $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$ holds. Results are available on request.

[17] With the same α as above. Actually, the limit $|\eta| < 2$ comes from the theoretical discussion. With the data from 2004-2010, $|\eta|$ can be larger and the inequality still holds. The results are available on request.

$\frac{\partial y}{\partial \alpha} > 0$. This means that the impact of the quota obligation on total electricity production is more sensitive to changes in b than to changes in η and in variables set by the market, i.e. p, p_{tgc} and D. We believe that $1.1 < b < 1.3$ is a reasonable estimate and therefore state that the impact of the quota obligation on the total electricity production is negative. This means that increasing the quota obligation decreases the total electricity production, and also that the decrease in black electricity is larger than the increase in the green electricity production.

6 Extending a market for TGCs

Now that we have studied a domestic TGC market, what happens if we extend the market to two countries with a common market for electricity, emission allowances and tradable green certificates? Since this market extension can be seen as the upcoming Swedish-Norwegian market, the analysis is carried out in this setting. In this market we assume the price of electricity and emission allowances to be exogenous, since the two countries will be part of a larger electricity and emission allowance market[18]. We study the impacts on the country with an existing TGC system (Sweden) when another country (Norway) enters the market. The analysis is divided into two scenarios and with the general model as starting point. The two scenarios differ in what expected effect the international market has on the TGC price, which is highly uncertain.[19] Scenario I assumes that an international market pushes down the TGC price, while scenario II assumes that an international market pushes up the TGC price. We will discuss the short- and long-term effects for each scenario, and the results are summarized in Table 2 in Section 7.

The model in the short run

First, we recap the derivatives with the short-run assumptions,[20]

$$\frac{\partial y_b}{\partial \alpha} = \frac{-y\frac{\partial p}{\partial y} + (1-\alpha)p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0, \qquad \frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0,$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p - (1-\alpha)y\frac{\partial^2 c_b}{\partial y_b^2} + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}}, \qquad \frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0,$$

$$\frac{\partial y}{\partial \alpha} = \frac{-(1-\alpha)^{b-1}b(b-1)D^{b-1}p^{(b-1)\eta} + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}}, \qquad \frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\gamma}{\frac{\partial p}{\partial y} - (1-\alpha)^2\frac{\partial^2 c_b}{\partial y_b^2}} < 0.$$

We see that regarding the impacts of the ETS price, nothing changes with the TGC price. The impact of the ETS price on black, green and total electricity

[18] This will be the case in the Swedish-Norwegian market. The electricity price is set on the Nordic market, which comprises Norway, Sweden, Finland and Denmark. Further, the northern European market is linked to this market. The emission allowances are part of the EU ETS, with allowances valid in 30 European countries.

[19] This will be exemplified below when presenting the scenarios.

[20] The short run assumptions are $\frac{\partial^2 c_g}{\partial y_g^2} = 0$, $\frac{\partial \gamma}{\partial p_{ets}} = 0$, $c_b = y^b$ with $b \approx 1.2$ and $y = Dp^\eta$ with $0.1 < |\eta| < 0.3$.

production is negative, so an increase in the ETS price decreases the production. This is in line with the result above for the closed TGC market. The result regarding the impacts of the quota obligation on the black electricity production is the same as for the domestic TGC market and independent of the development of TGC prices. For the other impacts of the quota obligation we need to divide the analysis into two scenarios.

Scenario I, an extended market pushes down the TGC price This scenario assumes that the opening of the TGC market pushes down the TGC price compared to the price in Sweden prior to the common market. This is a reasonable scenario, since Norway may have a surplus of TGCs as a result of its hydropower. Thus, p_{tgc} decreases compared to the closed market in the previous section. The denominator is still the same and negative, and hence we will study the numerator. For the production of green electricity, the only positive part of the numerator, αp_{tgc}, is smaller than before. However, the sign of the impact on the green electricity production in the domestic market is undetermined, without using the assumption $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$. When studying the historical time series, we saw that the impact on the green electricity production is positive since we observed that $\left|\frac{1}{\eta}p\right| > \alpha p_{tgc}$. Based on this, a smaller p_{tgc} also leads to a positive impact on the green electricity production, conditional on that p is the same. An indirect effect of changes in p_{tgc} is of course also possible, leading to a decrease in the price of electricity. Yet, this potential is much smaller than the direct effect on the TGC price.[21]

For the impact on the total production, the discussion is similar to the one above. The only positive part of the numerator, αp_{tgc}, is smaller than before and if there are no changes to the negative term, then the impact will still be positive. However, as before, there might be indirect effects on the price of electricity, p, and on D[22] that will change the size of the negative part of the impacts on the total electricity production. We study the included terms in the numerator and test the sensitivity of the impacts of the included parameters[23] on the total electricity production. We conclude that the impact on the total electricity production is negative also in this case. Let us now move on to scenario II.

Scenario II, an extended market pushes up the TGC price This effect may be due to a shortage of TGCs in Norway, maybe a resulting from a too sparse allocation of TGCs. Therefore, p_{tgc} increases compared to the closed market and again we will discuss the numerator of the terms. For the impact on the green and total electricity production, the only positive term, αp_{tgc}, has increased and there may also be changes in the negative terms due to indirect effects on p. Thus, we are not able to determine the sign of the impacts on the green or the total electricity production.

[21] This depends on how sensitive the price of electricity is to changes in the TGC price. In the Swedish-Norwegian case this effect will be small since the prices of both electricity and ETS are set on a bigger market.

[22] Since $D = \frac{y}{p^{\eta}}$, indirect effects in production will change the size of D.

[23] D, b, α and η.

The model in the long run

We start with the derivatives with the long-run assumptions,[24]

$$\frac{\partial y_b}{\partial \alpha} = \frac{y\alpha\frac{\partial^2 c_g}{\partial y_g^2} - \frac{1}{\eta}p + (1-\alpha)p_{tgc}}{\frac{\partial p}{\partial y} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0, \qquad \frac{\partial y_b}{\partial p_{ets}} = \frac{(1-\alpha)^2\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0,$$

$$\frac{\partial y_g}{\partial \alpha} = \frac{\frac{1}{\eta}p + \alpha p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2\frac{\partial^2 c_g}{\partial y_g^2}}, \qquad \frac{\partial y_g}{\partial p_{ets}} = \frac{\alpha(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0,$$

$$\frac{\partial y}{\partial \alpha} = \frac{\alpha y\frac{\partial^2 c_g}{\partial y_g^2} + p_{tgc}}{\frac{\partial p}{\partial y} - \alpha^2\frac{\partial^2 c_g}{\partial y_g^2}}, \qquad \frac{\partial y}{\partial p_{ets}} = \frac{(1-\alpha)\left(\gamma + p_{ets}\frac{\partial \gamma}{\partial p_{ets}}\right)}{\frac{\partial p}{\partial y} - a^2\frac{\partial^2 c_g}{\partial y_g^2}} < 0.$$

And as for the short-run analysis, we see that all results for the impacts of the ETS price as well as the impact of the quota obligation on the black electricity are consistent with those for the domestic TGC market.[25] For the impacts of the quota obligation on the green and total electricity production, we need the two scenario analyses.

Scenario I, an extended market pushes down the TGC price We will now revisit scenario I, where p_{tgc} decreases compared to the closed market in the previous section. With a decrease in p_{tgc}, we see that, regarding the impacts on the green electricity production, the positive term, αp_{tgc}, decreases. The negative part, $\frac{1}{\eta}p$, may also be indirectly affected by changes in p_{tgc}, giving a decrease in the price of electricity. However, this effect is much smaller than the direct effect on the TGC price. Based on the findings in Section 5, we have a positive impact on the green electricity production, meaning that the production of green electricity increases when the quota obligation increases.

When it comes to the impact on the total electricity production, we see that the terms in the numerator are still positive, yet the magnitude of p_{tgc} has increased. This means that the impact on the total electricity production is still negative, and hence that the total production of electricity will decrease when the quota obligation increases. Summarizing the results, we see that if the international market pushes down the TGC prices, the impacts on electricity production are the same as in the domestic TGC market case. An increase of the quota obligation increases the production of green electricity and decreases the black electricity production and the total electricity production. Let us now move on to scenario II.

Scenario II, an extended market pushes up the TGC price We will now revisit scenario II, where extending the market for TGC pushes up the price of TGCs, as discussed above. For the total production, we see that the

[24] The long run assumptions are $\frac{\partial^2 c_b}{\partial y_g^2} = 0$, $\frac{\partial \gamma}{\partial p_{ets}} < 0$ and $y = Dp^{\eta}$ with $0.3 < |\eta| < 2$.

[25] For the impacts of the ETS price this is conditional on the assumption of inelastic demand for CO_2 emissions, and we see no reason for this to change when extending the market for TGCs.

impact is still negative. When it comes to the impact on the green electricity, we see that we may have a shift here. Before, we had that the impact was positive since $\frac{1}{\eta}p > \alpha p_{tgc}$, but now as αp_{tgc} is increasing we see that depending on the magnitude of p_{tgc}, maybe the impact will shift sign and become negative. The price of the electricity production may also be affected as an indirect effect of the price changes of the TGCs. According to this, the sign of the impact on the green electricity production will be ambiguous, and will depend on the interrelation between αp_{tgc} and $\frac{1}{\eta}p$.

7 Results and discussion

Table 2 summarizes the results from the above sections. We can see that contrary to many other studies, we are able to determine the signs of most of the derivatives. The signs are persistent for the different time horizons and for the different market settings, which is promising. The underlying assumptions should however be kept in mind when reading the table. The parentheses indicate that the result is based on assumptions using empirical data.

Table 2: Summary of the results.

	General model	Domestic TGC market		Trade in TGC			
				scenario I		scenario II	
		short	long	short	long	short	long
$\frac{\partial y_b}{\partial \alpha}$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y_g}{\partial \alpha}$	?	(+)	(+)	(+)	(+)	?	?
$\frac{\partial y}{\partial \alpha}$	?	$(-)$	$-$	$(-)$	$-$	?	$-$
$\frac{\partial y_b}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y_g}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$
$\frac{\partial y}{\partial p_{ets}}$	?	$-$	$-$	$-$	$-$	$-$	$-$

For the domestic market, we have very clear results that are consistent over time. For the impacts of changes in the quota obligation, we see that the total production decreases even though the production using renewable resources increases. This means that the decrease in black electricity production is larger than the increase in green electricity production. For the impacts of changes in the ETS price on electricity production, we see that both types of electricity production and the total electricity production will decrease. Also, the largest decrease occurs in the production of black electricity. As discussed before, the decrease in the production of green electricity is unexpected and shows the danger of combining policy instruments. When it comes to the market with trade, we observe some question marks in Table 2. Even though these question marks are still worrying (and dissatisfying), they show up for less important results, since we believe that long-run effects are more important than short-run effects.

Comparing our results with the results from previous research we see that they are consistent, with the common feature of fewer clear results. The reason that we are able to determine the signs of more impacts, we believe is due to the assumptions made and the division of the analysis into a short and a long run. Hence, we include more assumptions than some other studies, without losing accuracy in the analysis. For instance, Amundsen and Nese (2009) are not able to determine a distinctive impact of the quota obligation on green electricity production or total production. When it comes to the market with trade, it is hard to compare our results with Amundsen and Nese (2009) since the ways the problem is tackled differs. Also Fisher (2009) studies the impacts of the quota obligation and gets similar results for black electricity, but has problems with the impacts for green electricity. Comparing our result with Amundsen and Mortensen (2001), that also have a division into short and long run, show some consistency but the comparison is not straightforward since the underlying assumptions differ. Worth noting is that for the impacts of changes in the ETS price, the price elasticity for CO_2 emissions is driving the results. For the impacts of the quota obligation, the driving force depends on the production of interest. For the total production in the short run it is b (the exponent in the cost function) while for the green electricity the result depends on the relationship between the prices of electricity and TGC. We believe that there are still questions that need more research within this area, both theoretical and empirical. For instance, studies of the outcome of the Swedish-Norwegian market and further extensions of the TGC market are interesting areas.

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