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ARILD HEIMVIK AND EIRIK S. AMUNDSEN

PRICES VS. PERCENTAGES: USE OF TRADABLE GREEN CERTIFICATES AS AN INSTRUMENT OF GREENHOUSE GAS MITIGATION

Department of Economics
UNIVERSITY OF BERGEN

Prices vs. percentages: Use of tradable green certificates as an instrument of greenhouse gas mitigation

By

Arild Heimvik[1] and Eirik S. Amundsen[2]

Abstract

The paper analyzes the problem of achieving a target path of emission reductions in the electricity sector, using a scheme of tradable green certificates (TGC). There are two types of generation, renewable and fossil. The latter causes the emissions. The paper also examines effects from emission regulation on construction of new renewable generation capacity. Outcomes are compared with an emission fee and a subsidy. The analytical results are simulated with a numerical model and social surplus are calculated for the different instruments. Two versions of the percentage requirement are devised for the TGC scheme. Results show that the target path of emission reductions is achievable, but incentives for new renewable generation capacity will be sub-optimal, regardless of the version of the percentage requirement. The TGC scheme is neither the most accurate nor the most cost-efficient, instrument but it does lead to a smaller reduction of social surplus than a subsidy.

[1] Department of Economics, University of Bergen, e-mail: arild.heimvik@uib.no

[2] Department of Economics, University of Bergen and Department of Food and Resource Economics, University of Copenhagen. Address: Department of Economics, University of Bergen, Box 7802, 5020 Bergen, Norway. Tel.: 004755589718, e-mail: eirik.amundsen@econ.uib.no

1. Introduction

Tradable green certificate schemes (TGC) are primarily used for stimulating the construction of new renewable electricity generation capacity, but the main objective behind such measures is to replace fossil-based electricity generation with emission free technologies. In this paper, we analyze the effect of a tradable green certificates (TGC) scheme over time and examine how well suited it is in achieving a specific target path of emission reductions. By assumption, the regulator seeks to reduce emissions in the electricity sector where emissions originate from electricity generated from fossil sources. The resulting regulation will affect generation of electricity from renewable sources. This is incorporated in the analysis by also examining the effect of the regulation on the construction of new green generation capacity. The performance of the TGC scheme is compared to the performance of an emission fee and a renewable subsidy. In our paper, we analyze two versions of the TGC scheme. First, we examine the common version where the regulator sets a target share of green electricity production out of total electricity demand. Then we look at a TGC scheme calibrated to achieve a specific target path of emission reductions exactly. An optimal policy instrument will bring about in both the target path of emission reductions and the associated optimal investment profile of new green generation capacity.

Choosing optimal instruments to achieve targets in environmental policy is a considerable challenge for regulators. Not only do they have a variety of different instruments to choose from, there may also be additional considerations than those related to environmental issues. Although this is an interesting topic, it will not be explored further here. Rather, we refer to others for contributions to this debate (Goulder & Parry, 2008, Löschel et al., 2010, Fischer & Preonas, 2010). In this paper, we confine ourselves to consider a specific target chosen by the regulator, and focus on how it can be achieved in a cost-efficient manner, using different economic instruments.

Previous research on the functioning of TGC schemes have mainly focused on the interplay of an existing electricity market and a market for green certificates (E. Amundsen, Baldursson, & Mortensen, 2006; Bye, 2003; Fischer, 2010). Others have expanded the analysis and included additional markets to assess the behavior of a TGC scheme (Eirik S Amundsen & Bye, 2018; Eirik S. Amundsen & Mortensen, 2001, 2002; Böhringer &

Rosendahl, 2010; Fischer & Preonas, 2010; Meran & Wittmann, 2012; Morthorst, 2001; Unger & Ahlgren, 2005). Earlier contributions to the literature, have applied a static model in their analyses. We do however, not know how a TGC scheme will behave over time and to the best of our knowledge, there are no papers analyzing this in a dynamic model. Our work can then be seen as theory contribution into the analysis of tradable green certificates. We are interested in seeing how well suited a TGC scheme is in achieving a specific target path of emission reductions. Such a dynamic target also corresponds to the target of GHG emission reductions set by the European Union. In addition, once introduced, a TGC scheme will be in effect for a number of years, making a dynamic analysis even more relevant. An examination of the performance of a TGC scheme in a dynamic setting is also interesting since many countries and regions around the world employ a version of such a scheme. Norway has a joint system with Sweden, while United Kingdom, Belgium and many states in the US[3] have introduced different types of quota obligations, to name a few. The idea of using a TGC scheme to reduce carbon emissions has been presented before (Aune, Dalen, & Hagem, 2012; Fischer & Newell, 2008; Palmer & Burtraw, 2005), but we have not come across any papers that have approached the subject in a dynamic setting under the same conditions as we do.

The discussion of optimal instrument choice in environmental policy has been going on for quite some time. Since the introduction of the concepts of external effects and correcting taxes by Arthur Pigou, there have been many articles on the subject. A notable mention is the seminal article by Weitzman (1974), that focused on the merits of taxes versus tradable emission permits. Since then, there have been many contributions to the literature of optimal instrument choice (Dröge & Schröder, 2005; Fell, Mackenzie, & Pizer, 2012; Goulder & Parry, 2008; Hepburn, 2006; Hoel & Karp, 2001; Newell & Pizer, 2003; Pizer, 2002; Stavins, 1996). In our paper, we compare the performances of different economics instruments in achieving a dynamic target of emission reductions and our work is a contribution to this strand of literature as well as the TGC literature.

The article is structured as follows: Section 2 presents the theoretical model, along with the assumptions made. Section 3, first examines a base scenario where there are no regulations.

[3] In the US, the system of tradable green certificates is known as renewable portfolio standard (RPS).

Then the solutions from social optimum, under regulation are derived. Thereafter, the paper proceeds to analyze how the different economic instruments perform in achieving the target set by the regulator. The discussion of the results takes place in section 4, and in order to provide some clear-cut results, we perform simulations, based on results from the theoretical model. Section 5 summarizes the discussions and provides some concluding remarks.

2. The model

The model, focuses on the electricity market, where there are two kinds of electricity generation, one based on renewable sources (green electricity) and one based on fossil sources (black electricity). The latter is the cause of pollution. For simplicity, we assume a one-to-one relationship between black electricity generation and pollution. Reductions of emission, therefore, happens through reduction of black electricity generation. We assume perfect competition in the electricity market and furthermore, for simplicity, that there are no distribution costs.

In accordance with established policies such as the EU target for emission reductions, we focus on a quantity target where the regulator wants to reduce the levels of CO2-emissions through a specific path. In our model, the regulator specifies a target path of emission stemming from black electricity generation. This mirrors the mechanisms of the emission permit market of EU-ETS. There, the regulator implements an annual percentage reduction for emissions. A binding reduction raises the permit price and drives down polluting electricity generation, achieving the desired emission reduction path[4][5].

The model is dynamic and incorporates construction of new green generation capacity, as well as physical depreciation of existing green generation capacity Technological progress in green generation capacity is included to capture the cost reductions in several green

[4] An alternative to a quantity target is the implementation of a price target, with a specified price path for CO2-emissions. This could be achieved with different instruments, but the resulting emission quantities would differ. Since the primary policy goal is normally a quantity target, this will be our focus in the paper as well.
[5] In our model, we do not include a damage function to describe the development of emissions over time. A damage function consists of emissions from several sectors, whereas our focus is on emission and regulations in the electricity market. The use of a damage function would therefore be inaccurate for our paper.

technologies in recent years (notably for PV technologies[6]). Technological progress is exogenously given and time dependent. Technically, in the model formulation to follow, the capacity of green generation capacity represents the state variable, whereas the investment in new green generation capacity represents the control variable.

We assume that the generation of green electricity always takes place at full capacity utilization. The rationale for this is that the marginal costs of electricity generation from the most mature technologies such as wind power are very low and close to zero. In accordance with this, we assume zero short run (operating) generation costs of green electricity generation. Hence, it is costless to use existing green generation capacity; only additional green generation capacity and maintenance of capacity carry a cost.

The following symbols and functional expressions are applied in the model.

p_t: Price of electricity at date t, net of distribution costs

q_t: Wholesale price if electricity at date t

y_t: Generation of black electricity at date t

$\bar{z}_t$: Green generation capacity at date t

x_t: Consumption of electricity at date t

k_t: Physical investment in new green generation capacity at date t

α_t: Percentage requirement at date t

r: Social discount rate

ρ: Rate of technological change

κ: Depreciation rate of green generation capacity

T: Termination date of problem considered

s_t: Price of green certificates at date t

τ_t: Emission fee at date t

σ_t: Subsidy at date t

[6] The price of solar PV module costs have decreased around 80 % from the end of 2009 through the end of 2015. The costs are projected to decrease further, around 42 % from 2015 to 2025 (http://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025 ,retrieved 20.04.2018)

$p(x_t)$: Time invariant inverse demand function for electricity, with $\frac{\partial p_t}{\partial x_t} < 0$

$c(y_t)$: Cost function for generation of black electricity , with $\frac{\partial c}{\partial y_t} > 0$ and $\frac{\partial^2 c}{\partial {y_t}^2} \geq 0$

$g(\bar{z}_t)k_t e^{-\rho t}$: Cost function for green generation capacity, with $g'(\bar{z}_t) > 0$ and $g''(\bar{z}_t) \geq 0$

k_t: Investment in green generation capacity in period t, with. $k_t \geq 0$

$\dot{\bar{z}}_t = k_t - \kappa\bar{z}_t$

$x_t = y_t + \bar{z}_t$

$\bar{z}_t = \alpha_t x_t$

$y_t = (1 - \alpha_t)x_t$

$\bar{y}_t = y_0 e^{-\chi t}$: Target path of emission reductions, developed exogenously by the regulator

3. Analysis

3.1. Base scenario - no regulation

In the base scenario, there are no regulations or targets imposed by the regulator. The optimization problem for the generators is

$$\max \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

subject to

$$\dot{\bar{z}}_t = k_t - \kappa\bar{z}_t$$

The constraint expresses that the development in green generation capacity is determined by the difference between investment in new green generation capacity and the depreciation of existing capacity.

Denoting the co-state variable λ_t, the corresponding present value Hamiltonian to this problem reads

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \lambda_t(k_t - \kappa\bar{z}_t)$$

The first order conditions are

1) $\frac{\partial H_t}{\partial y_t} = [p_t - c'(y_t)]e^{-rt} = 0$

2) $\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \lambda_t = 0$

3) $\frac{\partial H_t}{\partial \bar{z}_t} = [p_t - g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \lambda_t \kappa = -\dot{\lambda}_t$

4) $\lambda_T \geq 0$

5) $H_T = [p(x_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T]e^{-rT} + \lambda_T(k_T - \kappa\bar{z}_T) = 0$

Differentiating 2) with respect to time, we arrive at

6) $-[g'(\bar{z}_t)e^{-\rho t}(k_t - \kappa\bar{z}_t) - \rho g(\bar{z}_t)e^{-\rho t}]e^{-rt} + r[g(\bar{z}_t)e^{-\rho t}]e^{-rt} = -\dot{\lambda}_t$

Equalizing 6) with 3) we derive the optimality condition for the price of electricity

7) $p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$

Furthermore, from 1), the price of electricity must satisfy

8) $p_t = c'(y_t) = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$

Without regulation, the price of electricity equals the marginal costs of black electricity generation. This will again be equal to the (annualized) marginal costs of green electricity generation. As shown in Appendix A, the electricity price will decrease over time along with an increasing consumption of electricity. Furthermore, the generation of black electricity will decrease over time whereas the generation of green electricity will increase along with technological progress. The increasing generation of green electricity will more than outweigh the decreasing generation of black electricity. If there is no technological progress ($\rho = 0$), then price, consumption and black and green electricity generation will be constant over time.

Hence, even in the unregulated case, the generation of black electricity – and therefore emissions – will also fall over time as investments in green generation capacity become cheaper. However, the reduction of emission may fall short of the target, wherefore additional regulation will be called for.

3.2. Social optimum under regulation

The regulator now seeks to achieve a specific target path of emission reductions by reducing the generation of black electricity. In a market with two types of generation technologies, a reduction of black electricity generation will affect investments in new green generation capacity. Hence, the target path for emission reductions will give rise to a specific associated investment profile of new green generation capacity. The solutions attained under regulation in this section are henceforth referred to as solutions of the social optimum (i.e. to avoid the use of the more correct but more cumbersome term "emission constrained social optimum")

The regulator faces the following optimization problem

$$\max \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

subject to

$$\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$$
$$y_t \leq \bar{y}_t$$

The first constraint is the same as before. The second constraint expresses the optimal emission reductions. We assume this constraint is binding, i.e. the generation of black electricity is always less than the generation of black electricity in the unregulated case.

Denoting the co-state variable β_t and the shadow price of the generation constraint by ω_t, the corresponding present value Hamiltonian to this problem reads

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \beta_t(k_t - \kappa\bar{z}_t) + \omega_t(\bar{y}_t - y_t)$$

The first order conditions are

9) $\frac{\partial H_t}{\partial y_t} = [p_t - c'(\bar{y}_t)]e^{-rt} - \omega_t = 0$

10) $\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \beta_t = 0$

11) $\frac{\partial H_t}{\partial \bar{z}_t} = [p_t - g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \beta_t\kappa = -\dot{\beta}_t$

12) $\beta_T \geq 0$

13) $H_T = [p(x_T)x_T - c(\bar{y}_T) - g(\bar{z}_T)e^{-\rho T}k_T]e^{-rT} + \beta_T(k_T - \kappa\bar{z}_T) + \omega_T(\bar{y}_T - y_T) = 0$

Following the same approach as in section 3.1., the price of electricity in social optimum may be expressed as

14) $p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} = c'(\bar{y}_t) + \omega_t e^{rt}$

Also for this case, the price of electricity will be equal to the (annualized) marginal costs of green electricity generation, which is also equal to the marginal costs of the regulated generation of black electricity, and a shadow price linked to the quantity constraint. As shown in Appendix B, the electricity price will increase over time when there is no technological progress ($\rho = 0$). In this case the generation of green electricity increases over time (with investments above depreciation) while the black electricity generation decreases over time in accordance with the regulation. In sum, total electricity generation falls over time. However, in the case of technological progress for green generation capacity, the electricity price development is indeterminate. Nevertheless, even in the case of a decreasing electricity price it is a robust conclusion that the generation of green electricity must increase over time. This must be so since a decreasing electricity price necessitates an increasing generation of green electricity when the generation of black electricity is decreasing and the demand function is assumed time invariant.

In order to highlight the time path of investment of new green generation capacity, we differentiate 14) to obtain

$$15)\ k_t = \frac{-\frac{\partial p_t}{\partial x_t}(\dot{\bar{y}}_t - \kappa \bar{z}_t) - [(r+2\rho+2\kappa)\kappa \bar{z}_t g'(\bar{z}_t) + (\kappa \bar{z}_t)^2 g''(\bar{z}_t) + \rho(r+\rho+\kappa)g(\bar{z}_t)]e^{-\rho t}}{\frac{\partial p_t}{\partial x_t} - (r+\rho+2\kappa)g'(\bar{z}_t)e^{-\rho t} - \kappa \bar{z}_t g''(\bar{z}_t)e^{-\rho t}}$$

From this expression and as noted above, we see that the investment of new green generation capacity must be strictly positive. However, the actual path of investments is determined by the parameters of the model.

The next section examines if the various instruments can achieve the solutions of the social optimum. First, we analyze the case where the regulator chooses a TGC scheme as the preferred instrument. Then, we compare the results with the cases where the regulator uses an emission fee for black generators and a subsidy for green generators. An optimal instrument will achieve both the target path of emission reductions and the associated investment profile of new green generation capacity.

3.3. Market solution – TGC scheme

With a TGC scheme, a separate market for green certificates is created and linked to the electricity market. The supply of green certificates comes from new producers of renewable electricity who receive certificates corresponding to their amount of production $(\bar{z}_t)$. These certificates can be sold on the certificate market and is an extra source of income, together with the sale of electricity on the wholesale market. Since electricity is a homogenous good, the regulator must create a demand for green certificates to ensure a well-functioning market. Consumers of electricity are therefore obligated to have a specific share (the percentage requirement, α) of TGCs out of their total demand for electricity $(\alpha_t x_t)$. We assume that the capacity of generating green electricity is constraining. This can be expressed as $x_t = \frac{\bar{z}_t}{\alpha_t}$. The regulator determines the required share through the percentage requirement. The share increases over time to create a growing demand for green certificates. Each year, consumers with an obligation must redeem certificates corresponding to their obligation. For each certificate not redeemed, the consumers must pay a fine. The costs of the TGC scheme are then borne by the consumers who pay for it through their electricity bill. The aim is to make green electricity more competitive over time, and the types of technology that are most mature will enter the market through this scheme[7]. This will ensure the criteria of cost-efficiency. Even though a TGC scheme does not incur any direct taxes or subsidies, the new producers of electricity from renewable (non-fossil) sources receive a subsidy with the green certificates. Producers of electricity from fossil sources on the other hand, receive only the wholesale price of electricity, so for them a TGC scheme entails an implicit tax. It should, otherwise, be stressed that a TGC scheme is a self-contained system where the regulator (government) is not directly involved in giving subsidies and levying taxes. The only role of the regulator is to announcing the path of the percentage requirement, to issue certificates, and to control that producers and consumers comply with the system.

Previous contributions to the TGC literature have shown that polluting fossil energy production will decrease as the percentage requirement increases. While the effect of an increasing percentage requirement on green electricity generation is inconclusive, there will still be an increase in the share of renewables out of total demand for electricity (see e.g. Eirik S. Amundsen & Mortensen, 2001).

The end-user price of electricity with the TGC scheme is $p_t = q_t + \alpha_t s_t$, where q_t is the wholesale price of electricity, s_t is the price of the green certificate and α_t is the percentage requirement. The percentage can be expressed as

$$16)\ \alpha_t = \frac{\bar{z}_t}{\bar{z}_t + y_t}$$

In order to gain a better understanding of the TGC scheme, we analyze two versions with different percentage requirements. In the first version, the path of percentage requirements is derived from the target share in 16), where the values on the right hand side are derived in section 3.2. Hence, the share of green electricity out of total demand for electricity is set

[7] The system can be adapted to stimulate investments in less mature technologies by awarding more certificates to these types of technology. This concept of “banding” was a central feature in the Renewables Obligation scheme in the UK

equal to the share in the social optimum under regulation. This case corresponds to what one would expect regulators to do, i.e. to use the percentages from the optimal regulated social solution in the belief that this would result in the optimal regulated social solution. As shown below, however, it turns out that this is not the case. For this reason, we consider a second version, where the path of the percentage requirements is calculated to ensure that the target path of emission reductions is met explicitly.

Both versions of the percentage requirement originate from the same optimization problem and yield the same optimality conditions. The difference lies in the way that the percentage requirement is derived. Whereas we can calculate the first version explicitly, this is not possible for the second version.

For the remainder of this section, we focus on the first version while we return to the second version in section 4 when we illustrate the results, using a numerical model. Hence, in the following we treat the time path of the percentage requirement as given. It is calculated from the regulated social optimum by simply dividing the quantity of green electricity by the total quantity of electricity consumed at all times (i.e. from expression 16).

Differentiating 16) with respect to time provides the time path of the percentage requirement based on the optimal target share

$$17)\ \dot{\alpha}_t = \left(\frac{(k_t - \kappa\bar{z}_t)x_t - \bar{z}_t\left(\dot{\bar{y}} + (k_t - \kappa\bar{z}_t)\right)}{{x_t}^2}\right)$$

We know that $\dot{\bar{z}}_t > 0$, regardless of the presence of technological progress. It is however not given that $\dot{x}_t > 0$. If there is no technological progress (ρ = 0), then $\dot{\bar{x}}_t < 0$, this results in $\dot{p}_t > 0$ and $\dot{\alpha}_t > 0$. In the case of ρ > 0 however, we could have $\dot{x}_t > 0$ so that $\dot{p}_t < 0$. In this case, the time path of the percentage requirement is indeterminate. The exact shape of the path is determined by the relevant variables in the social optimum.

With a TGC scheme, the electricity generators face the following optimization problem

$$\max \int_0^T [(p_t - \alpha_t s_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + s_t\bar{z}_t]e^{-rt}$$

subject to

$\dot{\bar{z}}_t = k_t - \kappa\bar{z}_t$ and the derived path of percentage requirement from 17)

Denoting the co-state variable γ_t the corresponding present value Hamiltonian to this problem amounts to

$$H_t = [(p_t - \alpha_t s_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + s_t\bar{z}_t]e^{-rt} + \gamma_t(k_t - \kappa\bar{z}_t)$$

The first order conditions are

18) $\frac{\partial H_t}{\partial y_t} = [q_t - c'(y_t)]e^{-rt} = 0$

19) $\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \gamma_t = 0$

20) $\frac{\partial H_t}{\partial \bar{z}_t} = [q_t - g'(\bar{z}_t)e^{-\rho t}k_t + s_t]e^{-rt} - \gamma_t\kappa = -\dot{\gamma}_t$

21) $\gamma_T \geq 0$

22) $H_T = [(p_T - \alpha_T s_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T + s_T\bar{z}_T]e^{-rT} + \gamma_T(k_T - \kappa\bar{z}_T) = 0$

In order to obtain an expression for the TGC price, we differentiate 19) with respect to time, equalize it with 20) and use 18) to get

23) $s_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(y_t)$

The certificate price is thus the difference between the (annualized) marginal costs of green electricity generation and the marginal costs of black electricity generation. It functions to close the gap between the marginal costs of the two types of generation technologies.

The development of the certificate price is obtained by differentiating 23) with respect to time.

$$24)\ \dot{s}_t = k_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - \rho(r+\rho+\kappa)g(\bar{z}_t)e^{-\rho t} - \kappa\bar{z}_t[(r+2\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - c''(\bar{y}_t)\dot{y}_t$$

The expression shows that there are contending effects at work, resulting in an indeterminate effect over time. However, with no technological progress (ρ = 0), the price of the green certificates increases over time. If there is technological progress however, the difference between the marginal costs decreases and the necessary support for new green generation capacity is reduced, and thus resulting in an indeterminate path for the certificate price.

From 18), the wholesale price of electricity is equal to marginal costs of black electricity generation. Inserting 23) into 18) provides the optimality condition for the end-user price of electricity.

$$25)\ p_t = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + (1-\alpha_t)c'(y_t)$$

The end-user price of electricity is a weighted sum of (annualized) marginal costs of green electricity generation and marginal costs of black electricity generation, with the percentage requirement as the weight.

The price path can be inspected by differentiating 25) with respect to time to obtain

$$26)\ \dot{p}_t = \dot{\alpha}_t s_t + \alpha_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]\dot{\bar{z}}_t e^{-\rho t} - \alpha_t\rho(r+\rho+\kappa)g(\bar{z}_t)e^{-\rho t} + (1-\alpha_t)c''(y_t)\dot{y}_t$$

The end user price path with the TGC scheme is indeterminate. It does increase with the development of new green generation capacity, but we cannot determine the price path with certainty from the theoretical expression. This does not change even in the absence of technological progress. This stands in contrast to the results for the price path in the social optimum. The only result we can derive is in the special case where there is no technological progress and the marginal cost of black electricity generation is constant. Then, the price of electricity increases over time. The price path is investigated further in section 4 with a numerical model.

The relevant optimality conditions are summarized in table 1, for a comparison with the social optimum.

Table 1: Comparisons of optimality results for the TGC scheme

Social optimum	TGC
$p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$	$p_t = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + (1-\alpha_t)c'(y_t)$
$[p_t - c'(\bar{y}_t)]e^{-rt} - \omega_t = 0$	$[q_t - c'(y_t)]e^{-rt} = 0$
$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \beta_t = 0$	$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \gamma_t = 0$
$[p_t - g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \beta_t\kappa = -\dot{\beta}_t$	$[q_t - g'(\bar{z}_t)e^{-\rho t}k_t + s_t]e^{-rt} - \gamma_t\kappa = -\dot{\gamma}_t$

It is clear that the price of electricity under the TGC scheme can be equal to the price of electricity under the social optimum only if the percentage requirement is constant and equal to one. However, this contradicts with the path of the percentage requirement derived in 17), where the percentage requirement is not a constant. In addition, a percentage requirement equal to one implies that all supplied electricity is green. The regulator wants to achieve a specific reduction of black electricity generation but this target does not entail a complete phasing out.

Preliminary results show that the TGC scheme is not an optimal instrument. Applying the optimal percentages of green electricity from the social optimum do not seem to result in the solutions of the social optimum. Further investigation is required to determine if the implementation of such a scheme can achieve either the target of emission reduction or the associated investment profile in new green generation capacity.

An expression for investment in new green generation capacity is obtained by differentiating 25) with respect to time.

$$27)\ k_t = \frac{\dot{\alpha}_t s_t + \dot{y}_t\left((1-\alpha_t)c''(y_t) - \frac{\partial p_t}{\partial x_t}\right) - \alpha_t \rho (r+\rho+\kappa) g(\bar{z}_t) e^{-\rho t} + \kappa \bar{z}_t \left[\frac{\partial p_t}{\partial x_t} - \alpha_t (r+2\rho+2\kappa) g'(\bar{z}_t) e^{-\rho t} - \alpha_t \kappa \bar{z}_t g''(\bar{z}_t) e^{-\rho t}\right]}{\frac{\partial p_t}{\partial x_t} - \alpha_t [(r+\rho+2\kappa) g'(\bar{z}_t) + \kappa \bar{z}_t g''(\bar{z}_t)] e^{-\rho t}}$$

This expression is dependent on the endogenous variable $\dot{y}_t$. In order to eliminate it from the right hand side of the equation we use the equilibrium condition in the certificate market. Differentiating this with respect to time results in

$$28)\ k_t = \left(\frac{\dot{\alpha}_t}{(1-\alpha_t)^2}\right) y_t + \frac{\alpha_t}{(1-\alpha_t)} \dot{y}_t + \kappa \bar{z}_t$$

Equalizing 27) and 28) provides the following expression for development in black electricity generation – and thus pollution – with the TGC scheme

$$29)\ \dot{y}_t = \frac{\dot{\alpha}_t \left[(1-\alpha_t)^2 s_t - y_t \left(\frac{\partial p_t}{\partial x_t} - \alpha_t [(r+\rho+2\kappa) g'(\bar{z}_t) + \kappa \bar{z}_t g''(\bar{z}_t)] e^{-\rho t}\right)\right] - (1-\alpha_t)^2 \alpha_t \rho (r+\rho+\kappa) g(\bar{z}_t) e^{-\rho t} - (1-\alpha_t)^2 \kappa \bar{z}_t \alpha_t \rho g'(\bar{z}_t) e^{-\rho t}}{(1-\alpha_t)\left[\frac{\partial p_t}{\partial x_t} - \alpha_t^2 [(r+\rho+2\kappa) g'(\bar{z}_t) + \kappa \bar{z}_t g''(\bar{z}_t)] e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right]}$$

The expression above is indeterminate. Although the denominator is negative, the numerator is ambiguous. However, if there is no technological progress, the expression will be negative, i.e. the generation of black electricity – and consequently emissions – decrease over time.

A negative effect on black electricity generation is also in line with previous findings in the literature, where an increase in the percentage requirement is shown to have a negative effect on the generation of black electricity (see e.g. Eirik S. Amundsen & Mortensen, 2001).

Inserting 29) into 27) provides an expression of investment in new green generation capacity, determined by exogenous variables.

$$30)\ k_t = \frac{\dot{\alpha}_t\left(\alpha_t(1-\alpha_t)s_t - \left((1-\alpha_t)c''(y_t) - \frac{\partial p_t}{\partial x_t}\right)y_t\right) - {\alpha_t}^2(1-\alpha_t)(r+\rho+\kappa)\rho g(\bar{z}_t)e^{-\rho t}}{(1-\alpha_t)\left[\frac{\partial p_t}{\partial x_t} - {\alpha_t}^2(r+\rho)g'(\bar{z}_t)e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right]} + D^{8}$$

The denominator is negative, but the numerator is ambiguous. Unlike 29), this result does not change even if there is no technological progress (ρ = 0). In the model, investments are assumed non-negative, but from 30) it is not obvious that investments will lead to an increase in new green generation capacity over time. A TGC scheme is designed to achieve a certain share of electricity from renewable sources out of total demand. In theory, this could be achieved by a reduction of black electricity generation alone.

In section 4, we explore further, how investments under the TGC scheme evolve over time, using a numerical model. It is however clear that when the regulator uses a TGC scheme, with a percentage requirement based on 16), neither the target path for emission reductions nor the associated optimal investment profile in new green generation capacity is obtained. Hence, if it is imperative that the target of emission reductions is achieved over time, a TGC scheme based on the percentage requirements as calculated by 16 cannot be acceptable. For this reason, we continue the analysis of the TGC scheme in section 4, where we calculate percentage requirements that *will* achieve the targeted emission reductions, and study the investment profile of new green capacity that follows from this constraint. To gain insight, we compare, however, with the effects of using two alternative instruments i.e. an emission fee and a direct subsidy scheme.

3.4. Market solution – emission fee

The emission fee is imposed on generators of black electricity for each unit of output. The optimization problem for the generators reads

$$\max \int_0^T [p(x_t)x_t - c(y_t) - \tau_t y_t - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

[8] Due to space restrictions, the term D is written in its entirety in the appendix C

subject to

$$\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$$

Denoting the co-state variable ϵ_t, the present-value Hamiltonian takes the following form

$$H_t = [p(x_t)x_t - c(y_t) - \tau_t y_t - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \epsilon_t(k_t - \kappa \bar{z}_t)$$

The relevant optimality conditions are summarized in table 2.

Table 2: Comparisons of optimality results for the emission fee

Social optimum	Emission fee
$p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa \bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$	$p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa \bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$
$[p_t - c'(\bar{y}_t)]e^{-rt} - \omega_t = 0$	$[p_t - c'(y_t) - \tau_t]e^{-rt} = 0$
$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \beta_t = 0$	$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \epsilon_t = 0$
$[p_t - g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \beta_t \kappa = -\dot{\beta}_t$	$[p_t - -g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \epsilon_t \kappa = -\dot{\epsilon}_t$

It is evident that, the emission fee is able to replicate the optimality conditions from the social optimum. The reductions in emission and the associated investments in new green generation capacity are therefore equal to the solutions from the social optimum.

Applying the first order conditions from table 2 in the same manner as before provides an expression for the emission fee.

31) $\tau_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa \bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(\bar{y}_t)$

The emission fee, levied on black electricity generators, is the difference between (annualized) marginal costs of green electricity generation and marginal costs of black electricity generation.

In order to investigate the path of the emission fee over time, we differentiate 31) with respect to time to obtain

32) $\dot{\tau}_t = k_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - \rho(r+\rho+\kappa)g(\bar{z}_t)e^{-\rho t} - \kappa\bar{z}_t[(r+2\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - c''(\bar{y}_t)\dot{\bar{y}}_t$

The emission fee necessary to achieve the target set by the regulator increases over time as long as there is no technological progress. In the presence of technological progress, however, the expression above is indeterminate. When green generation capacity becomes cheaper, it might well be sufficient with a lower emission fee over time, in order to achieve the same target.

Since the emission fee is an optimal policy instrument, the investment profile in new green generation capacity is equal to the solution in the social optimum, derived in 15).

3.5. Market solution – subsidy

As an alternative to an emission fee, the regulator can award a subsidy to generators of green electricity in order to displace generation of black electricity.

The producers in the maximize the following optimization problem

$$\max \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + \sigma_t\bar{z}_t]e^{-rt}$$

subject to

$$\dot{\bar{z}}_t = k_t - \kappa\bar{z}_t$$

Denoting the co-state variable δ_t, the present-value Hamiltonian reads

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + \sigma_t\bar{z}_t]e^{-rt} + \delta_t(k_t - \kappa\bar{z}_t)$$

Relevant optimality conditions are listed in table 3 for a comparison with the social optimum.

Table 3: Comparisons of optimality results for the subsidy

Social optimum	Subsidy
$p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$	$p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - \sigma_t$
$[p_t - c'(\bar{y}_t)]e^{-rt} - \omega_t = 0$	$[p_t - c'(\bar{y}_t)]e^{-rt} = 0$
$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \beta_t = 0$	$-[g'(\bar{z}_t)e^{-\rho t}]e^{-rt} + \delta_t = 0$
$[p_t - g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \beta_t\kappa = -\dot{\beta}_t$	$[p_t - g'(\bar{z}_t)e^{-\rho t}k_t + \sigma_t]e^{-rt} - \delta_t\kappa = -\dot{\delta}_t$

An implementation of a subsidy will not result in the socially optimal solution. Although the subsidy achieves target path of emission reduction the price of electricity is always lower than the socially optimal price. This creates excessive incentives for green electricity generators and the demand for electricity exceeds the level, which is optimal from the point of view of society.

The price of electricity with the subsidy is equal to marginal costs of black electricity generation. Differentiation of the optimality condition for the electricity price, with respect to time, shows that the price of electricity is monotonically decreasing.

33) $\dot{p}_t = c''(\bar{y}_t)\dot{\bar{y}}_t$

Following the same procedure as before by applying the first order conditions in table 3, results in an expression for the subsidy.

34) $\sigma_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(\bar{y}_t)$

The subsidy has the same structure as the emission fee. However, this does not mean that the two instruments are equal. Both the emission fee and the subsidy achieve the same path of emission reductions, but the subsidy also leads to increased consumption of electricity. This results in a subsidy that exceeds the level of the emission fee. A similar result is derived in Fischer and Newell (2008).

Differentiating 34) with respect to time, provides an expression for the time path of the subsidy.

$$35)\ \dot{\sigma}_t = k_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - \rho(r+\rho+\kappa)g(\bar{z}_t)e^{-\rho t} - \kappa\bar{z}_t[(r+2\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - c''(\bar{y}_t)\dot{\bar{y}}_t$$

Since the path of the subsidy is the same as for the emission fee, we know that the subsidy increases over time as long as there is no technological progress. With technological progress however, the gap between green and black marginal costs of electricity generation decrease over time, resulting in a reduction of the necessary subsidy and a path that is indeterminate.

The investment profile in new green generation capacity is obtained by differentiating the optimality condition for the electricity price, with respect to time.

$$36)\ k_t = \frac{\dot{\bar{y}}_t\left[c''(\bar{y}_t) - \frac{\partial p_t}{\partial x_t}\right] + \frac{\partial p_t}{\partial x_t}\kappa\bar{z}_t}{\frac{\partial p_t}{\partial x_t}}$$

Investments in new green generation capacity with the subsidy are unaffected by technological progress. The optimality condition for the price of electricity is determined solely by marginal costs of black electricity generation and the expression for the investment profile in new green generation capacity in 36) is derived from this optimality condition. In addition, depreciation results in higher investments, to replace existing green generation capacity.

4. Discussion

In order to make further progress in our analysis, we perform simulations based on the results from the analytical model. The functional forms used in this section can be found in appendix D. In addition, we compare the resulting social surplus from implementing the different policy instruments in order to assess their cost-efficiency. These results are summarized in table 4. In the simulations, the social discount rate is set to five per cent (r = 0,05) and the depreciation rate is set to 10 per cent (κ = 0,1). The figures also highlight the effect of increasing rate of technological progress. We have already shown that the emission fee results in the social optimum. Hence, a separate graph for the social optimum is not included in the figures.

Figure 1: Black electricity generation (emissions)

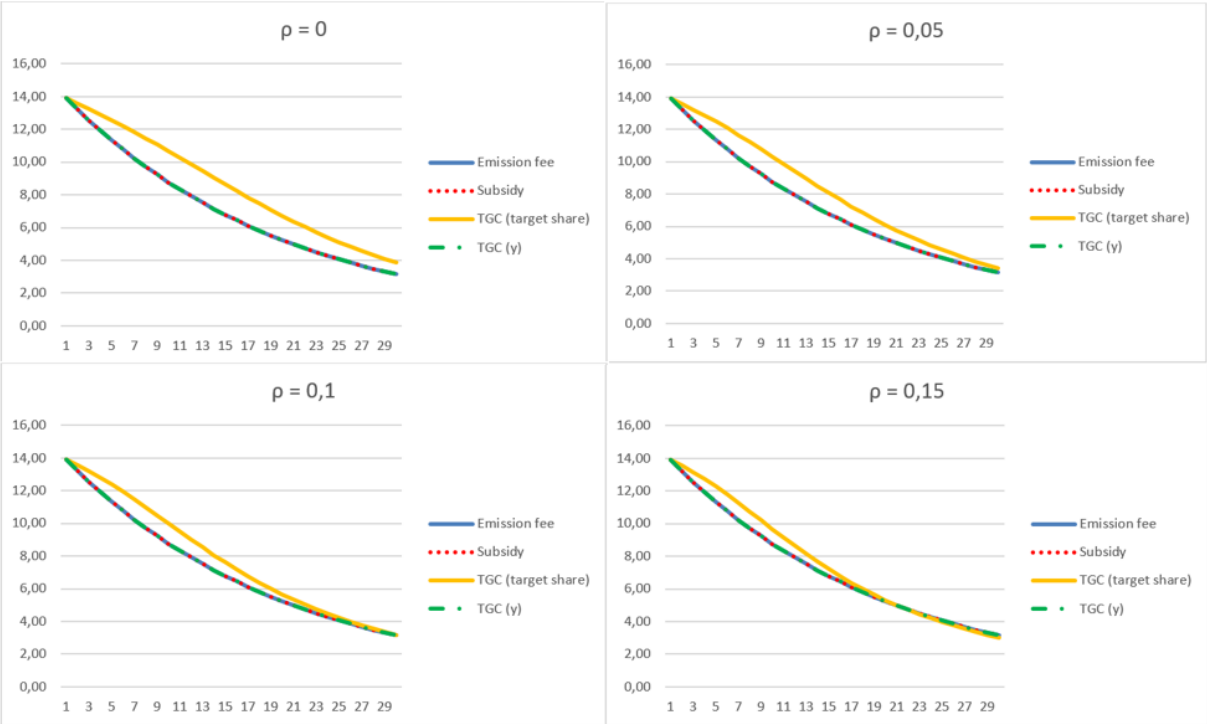


Figure 1 illustrates the performance of the different instruments in achieving the target path of emission reductions. As we saw from the theoretical model, the emission fee is an optimal instrument and achieves the target path of emission reductions. The subsidy is also capable of achieving the path of emission reductions, as is the TGC scheme (denoted TGC(y) in Figure 1), where the percentage requirements are determined such that generation of black electricity exactly gives the target path of emission reductions. More precisely, the regulator calculates an increase in new green generation capacity through the percentage requirements in order to displace generation of black electricity in accordance with the targeted path. Hence, both a pure fee, a pure subsidy and a TGC scheme can be adjusted such that the target path of emission reductions can be achieved.

However, if the regulator chooses a TGC scheme based on the percentage requirements from the emission constrained optimal solution as discussed in section 3.3. (denoted TGC (target shares) in Figure 1.), the result is a path of emission reductions that differs from the target path. In Figure 1, we see that the generation of black electricity in this case is falling over time (and therefore also the emission) irrespective of the strength of the technological progress. The path also lies above the generation path for black electricity in the other cases considered. However, this is not a general result. From the theoretical result in 29), we know that if there is no technological progress, black electricity generation decreases with certainty, but if there is technological progress then the path of black electricity generation is indeterminate.

Figure 2: Green generation capacity

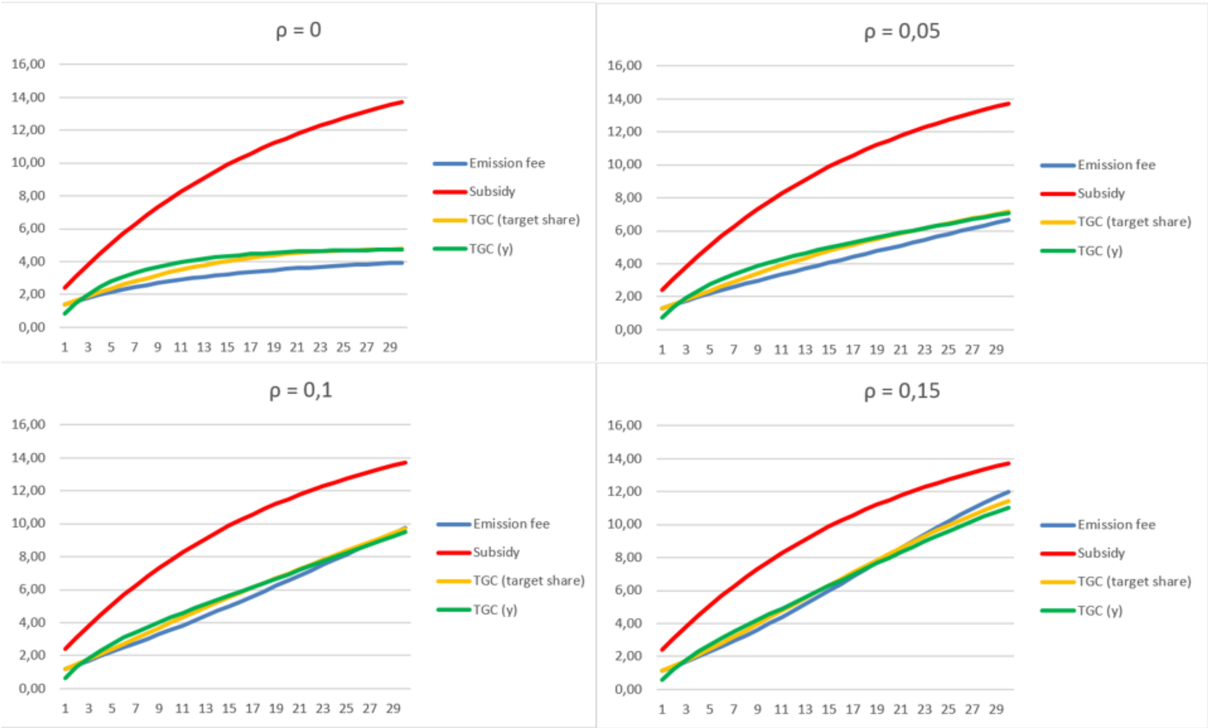


Figure 2 shows the development of green generation capacity. The graph for the emission fee represents the socially optimal development. As can be seen from the Figure, this graph gets steeper the larger is the technological progress. The graph for the subsidy lies above that of the emission fee, and is invariant to technological progress, since the investment profile for new green generation capacity is not determined by the cost function of green generation capacity. Hence, the subsidy displaces black electricity generation, but results in excess levels of green generation capacity.

For both versions of the TGC scheme, the levels of green generation capacity differ from the social optimum. Although the levels mostly exceed the socially optimal level, they can actually fall below, with increasing levels of technological progress. Comparing the investment profile in the social optimum and the TGC scheme in 15) and 30), the effect of the percentage requirement is apparent. The percentage requirement attenuates the parameters that affect investment since the percentage requirement takes a value between zero and one. Increasing rates of technological progress therefore has a lesser impact on the TGC scheme than the emission fee.

A comparison of Figures 1 and 2 also shows that as long as the generation of black electricity is above the target path for black electricity generation when using the TGC scheme based on the percentage requirements from the social optimum, the same will be the case for green generation capacity. Likewise, if black electricity generation falls below the target path, the path for the development of green generation capacity will lie below the path of the optimal green capacity development[9].

Figure 3: Investment in new green generation capacity

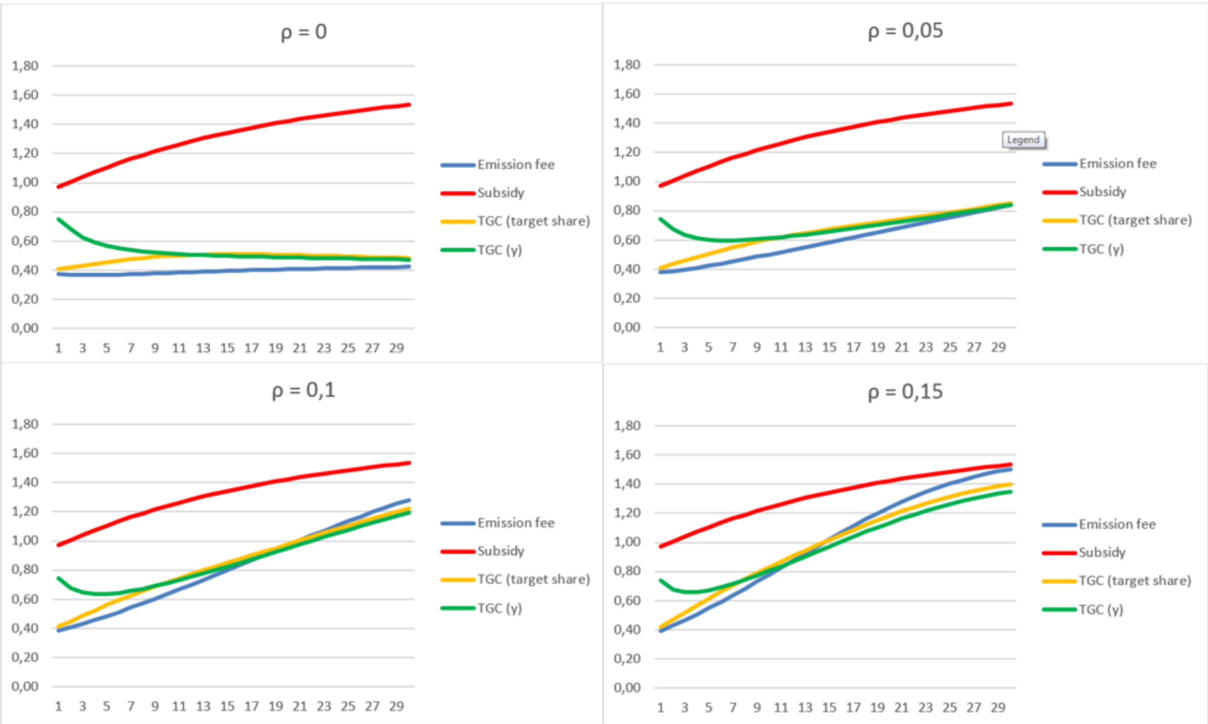


Figure 3 displays gross investments in new green generation capacity. The emission fee obtains the optimal investment path. In addition, the investment path gets steeper the

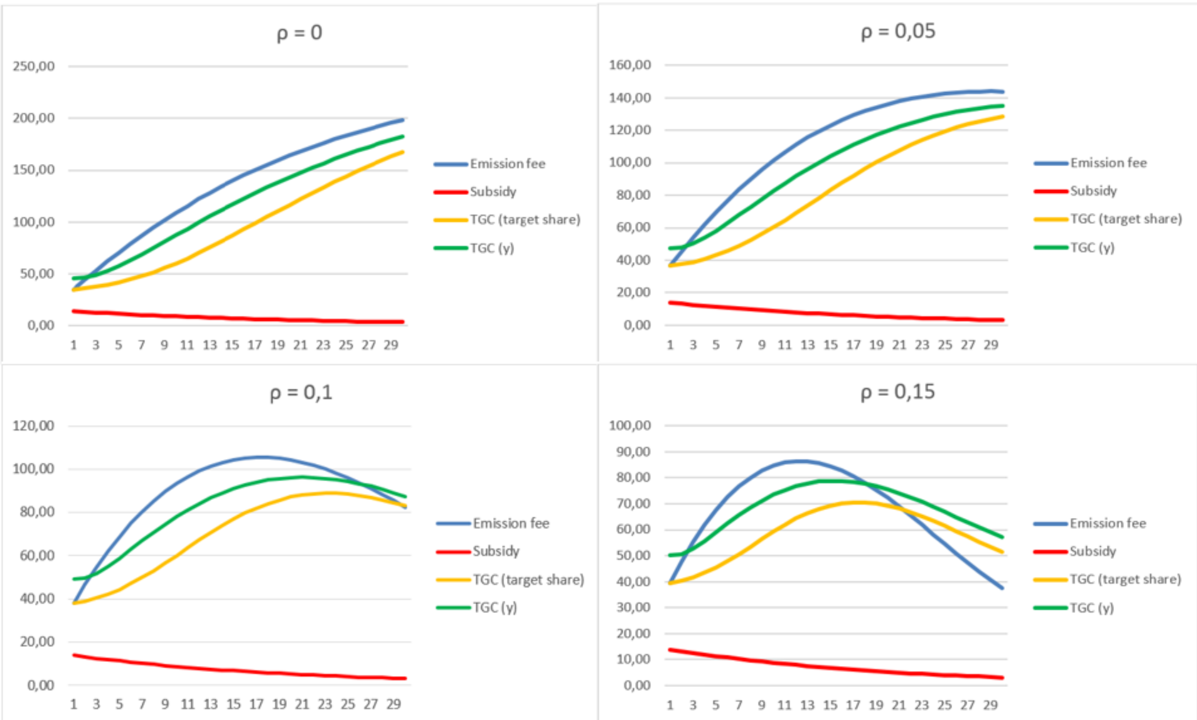
[9] This can be expressed mathematically by using the equilibrium condition for the certificate market

$$\frac{\alpha_t}{1-\alpha_t} y_t^{TGC} > \frac{\alpha_t}{1-\alpha_t} y_t^{SO} \Leftrightarrow \bar{z}_t^{TGC} > \bar{z}_t^{SO}$$

larger is the technological progress. Cheaper technology stimulates more investment. Investments are most extensive when the regulator uses a subsidy and the investment profile is unaffected by technological progress. This corresponds with the analytical result from 36).

Neither of the two versions of the TGC scheme give rise to the socially optimal investment levels in new green generation capacity. This confirms the result from Figure 2. The investment profiles also differ markedly between the two TGC schemes. Since the percentage requirement in the two cases are different by design, the investments profiles also differ as a result. From Figure 3 it is also clear that, depending on the rate of technological progress, the investment profiles of the TGC schemes can intersect with the socially optimal outcome. However, in such a case, the paths will be very different and the socially optimal level of green generation capacity is not attained at least cost with either of the TGC schemes.

Figure 4: Price of electricity



As predicted by the theoretical model, the emission fee results in the socially optimal price path. There is a monotonically increasing price as long as there is no technological progress.

With increasing rates of technological progress however, the price path can become strictly concave e.g. inversely U-shaped. From the optimality condition in 14), (annualized) marginal costs of green electricity generation determine the price of electricity. More affordable technology therefore can result in a price decrease of electricity over time.

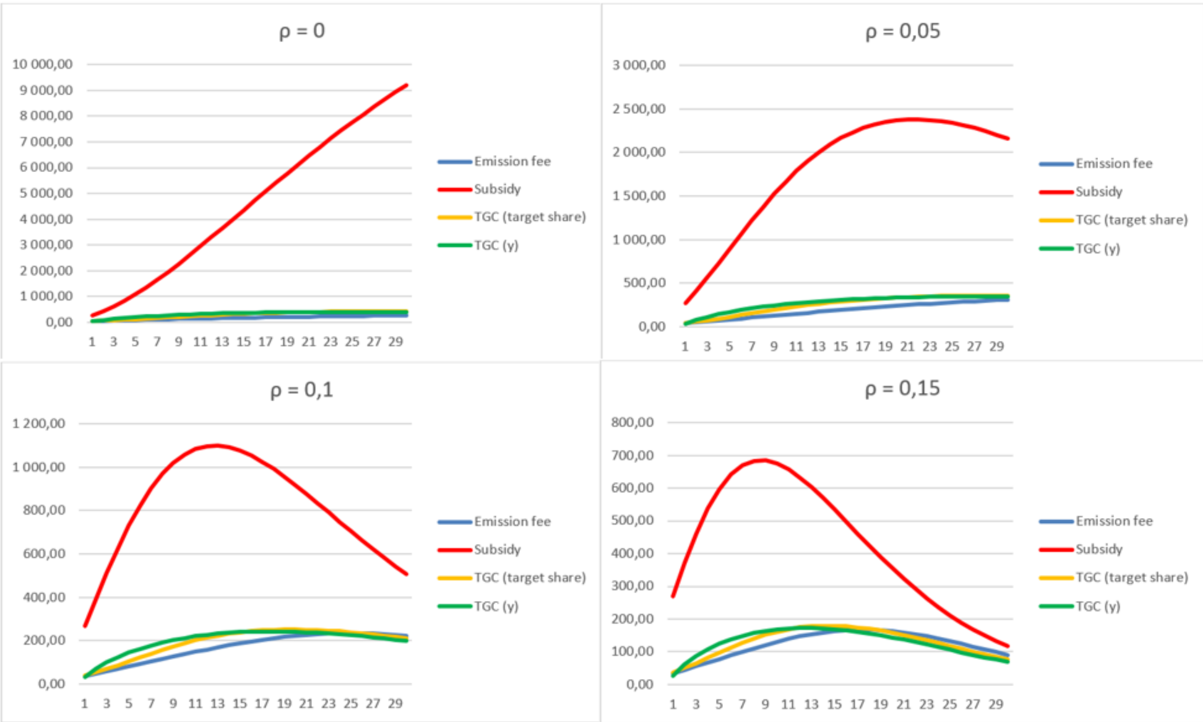
The subsidy results in the lowest price of electricity. Consequently, there will be excess demand for electricity compared to the optimal outcome. The price of electricity decreases over time and is invariant to technological progress; in line with our theoretical results.

With a TGC scheme where the percentage requirement is calculated from the socially optimal solution, the initial price equals the price in social optimum. This is a result of the equilibrium conditions in the certificate market. In a static model, Amundsen et.al. (2018), shows that total demand for electricity is higher with a TGC scheme than with an emission fee. From the theoretical results in this paper, a similar result is not as obvious. It is, however, clear that an important difference in the price paths comes from the effect of the percentage requirement. Since the percentage requirement is less than one, it dampens the effects that different parameters have on the price path with the TGC scheme, such as technological progress in green technology. This results in a price of electricity that could exceed the price in social optimum over time due to a reduced effect of cheaper green technology.

Another feature of the price path with the TGC scheme is that in contrast to the social optimum, it initially has a slower development, before the price increases more rapidly. Fischer (2010) shows that end-user prices can decrease for lower levels of the percentage requirement, whereas a more ambitious target results in price increases. Fischer points out that a TGC system combines a subsidy and an implicit tax. When the supply curve for black electricity is not completely flat, a subsidy will tend to reduce electricity prices. A tax on black electricity on the other hand tends to increase the end-user price. If the percentage requirement is low, there might be slight reductions in the end-user price of electricity. When the target becomes more ambitious, however, the implicit tax dominates, resulting in an increase of the end-user price of electricity.

If the TGC scheme has a path of percentage requirements computed to make sure that the target path of emission reductions is met explicitly, then the initial price level of electricity will differ from the social optimum. In this case, there is no direct link between the target share with the TGC scheme and the social optimum. However, both versions of the TGC scheme have a similar price path of electricity. This stems from the fact that both versions are derived from the same optimality conditions for the price of electricity. From figure 4, the price of electricity is consistently higher with the second version of the TGC scheme than if the percentage requirement is based on the shares calculated from the social optimum. From figure 1, it is clear that a percentage requirement derived from optimal target shares leads to too much generation of black electricity. This results in a price path that lies below the TGC scheme where the percentage requirement is computed to achieve the target path of emission reductions explicitly.

Figure 5: Costs of new green generation capacity



It is apparent from Figure 5 that increasing technological progress reduces costs, as green technology becomes cheaper. The graphs displayed in the Figure confirm that an emission fee is the optimal instrument in terms of cost-efficiency. The subsidy on the other hand leads to the highest costs, a result that does not change with technological progress. The optimal emission reduction is achieved, but the generous subsidy results in overinvestment in new green generation capacity and high costs in funding the subsidy.

Both versions of the TGC scheme result in higher costs than what would be the case if an emission fee were used instead. This is regardless of whether the target path of emission reductions is achieved or not. The cumulated costs are still higher with a TGC scheme. Nevertheless, as will become apparent from Table 4, either of the TGC schemes should be preferred to the subsidy, measured in terms of cost-efficiency.

Table 4: Final production levels and values of social surplus for the different policy instruments

	Target level of emissions $\bar{y}_T = 3,14$									
	Rate of tech. change	y_T			$\bar{z}_T$			W_T		
		κ = 0	κ = 0,05	κ = 0,1	κ = 0	κ = 0,05	κ = 0,1	κ = 0	κ = 0,05	κ = 0,1
Emission fee (τ)	**ρ = 0**	3,14	3,14	3,14	8,21	5,03	3,94	194 586,97 (100%)	268 013,31 (100%)	283 827,16 (100%)
	ρ = 0,05	3,14	3,14	3,14	9,94	7,80	6,67	184 864,70 (100%)	241 742,31 (100%)	263 091,47 (100%)
	ρ = 0,10	3,14	3,14	3,14	11,82	10,60	9,73	156 681,70 (100%)	203 920,56 (100%)	228 646,28 (100%)
	ρ = 0,15	3,14	3,14	3,14	12,95	12,43	11,99	127 367,96 (100%)	163 728,91 (100%)	187 041,42 (100%)
Subsidy (σ)	**ρ = 0**	3,14	3,14	3,14	13,70	13,70	13,70	13 295,60 (6,8%)	519,79 (0,2%)	-12 256,02 (- 4,3%)
	ρ = 0,05	3,14	3,14	3,14	13,70	13,70	13,70	16 812,79 (9,1%)	12 028,49 (5,0%)	7 244,18 (2,8%)
	ρ = 0,10	3,14	3,14	3,14	13,70	13,70	13,70	18 248,24 (11,6%)	16 227,67 (8,0%)	14 207,09 (6,2%)
	ρ = 0,15	3,14	3,14	3,14	13,70	13,70	13,70	18 907,24 (14,8%)	17 936,35 (11,0%)	16 965.46 (9,1%)
TGC (target share)	**ρ = 0**	3,48	3,70	3,85	8,91	5,83	4,77	122 406,22 (62,9%)	152 559,14 (56,9%)	153 058,86 (53,9%)
	ρ = 0,05	3,31	3,38	3,43	10,29	8,23	7,16	111 374,84 (60,2%)	134 875,96 (55,8%)	140 513,13 (53,4 %)
	ρ = 0,10	3,15	3,16	3,17	11,73	10,51	9,68	93 190,50 (59,5%)	113 895,69 (55,9%)	123 159,47 (53,9%)
	ρ = 0,15	3,05	3,02	3,00	12,54	11,91	11,43	76 123,43 (59,8%)	92 690,52 (56,6%)	102 597,00 (54,9%)
TGC ($\bar{y}$) [10]	**ρ = 0**	3,14	3,14	3,15	9,24	5,79	4,72	151 323,35 (77,8%)	164 020,58 (61,2%)	165 673,67 (58,4%)
	ρ = 0,05	3,14	3,15	3,16	10,32	8,12	7,08	120 735,41 (65,3%)	138 122, 00 (57,1%)	146 058,99 (55,5%)
	ρ = 0,10	3,13	3,14	3,15	11,51	10,24	9,48	92 705,46 (59,2%)	110 434,43 (54,2%)	121 630,99 (53,2%)
	ρ = 0,15	3,12	3,12	3,13	12,09	11,44	11,02	70 891,25 (55,7%)	85 179,32 (52,0%)	95 970,91 (51,3%)

The numbers in the three columns to the far right in Table 4 show the welfare effects from the different policy instruments[11]. The numbers in the parentheses show the attained share

[10] Due to rounding off in Excel, there are some minor deviations.

of social surplus compared to the social optimum. The formulas used to calculate the values are presented in appendix E.

The emission fee is the only instrument capable of attaining the maximum level of social surplus. An increase in technological progress results in a lower social surplus. Cheaper green technology leads to higher investments in new green generation capacity, creating a downward pressure on the electricity price. Increasing depreciation on the other hand, results in higher social surplus. It leads to lower net additions of new green capacity and increases the price of electricity.

The subsidy on the other hand provides the lowest social surplus. The social surplus increases in technological progress since the path of black electricity generation locks down the amount of new green generation capacity. Technological progress therefore only reduces costs. An increase in the depreciation rate on the other hand, has a negative effect on the social surplus. It leads to more replacement investments but it does not lead to more new green generation capacity, since this is determined by the level of black electricity generation. The price of electricity does not increase either, since it is determined by marginal costs of black electricity generation.

Neither version of the TGC scheme is able to attain the maximal social surplus, although both perform considerable better than the subsidy. As with the emission fee, the social surplus in both cases decreases with technological progress and increases in depreciation of existing green generation capacity. No consistent pattern emerges concerning which of the two versions produce the largest social surplus. This is contingent on the rates of technological progress and depreciation.

5. Summary and concluding remarks

In this paper, we analyze the effect of applying a TGC scheme in order to achieve a specific target path of emission reductions in the electricity sector. The market has two types of generation technologies; green and black, where black electricity generation causes the

[11] The values of social surplus in table 4 do not take into account the possible social gains that might stem from regulation. Such gains include the value from internalizing negative external effects as pollution.

pollution. We also examine the effects of regulation on the incentives for construction of new generation capacity from renewable sources. In order to assess the properties of a TGC scheme thoroughly, we analyze two versions, with differently derived percentage requirements. First, we examine a traditional version where the regulator calculates the percentage requirement as an optimal target share of green electricity out of total demand for electricity. Then, we analyze a version where the percentage requirement is computed to achieve the path of emission reductions explicitly. For comparison, we also analyze the cases where the regulator applies an emission fee and a subsidy to achieve the target path of emission reductions.

Our results show that it is possible to use either a TGC scheme, an emission fee, or a subsidy to achieve the target path of emission reductions. However, only the emission fee is an optimal policy instrument, achieving both the target path of emission reductions and the associated optimal investment profile in new green generation capacity.

Theoretical results in the paper show that only in the absence of technological progress will generation of black electricity fall with a TGC scheme. With technological progress, the results are indeterminate. However, a robust result from previous research shows that black electricity generation is reduced with an increase in the percentage requirement (see e.g. Eirik S. Amundsen & Mortensen, 2001). The numerical model shows that generation of black electricity is negatively correlated with an increase in the percentage requirement over time, but the resulting path of emission reductions, differ from the target path. In order to achieve the target set by the regulator, the percentage requirement must be derived to reduce generation of black electricity explicitly in accordance with the target path, by displacing black electricity generation with green electricity generation.

An optimal policy instrument results in both the target path for emissions as well as the associated optimal investments in new green generation capacity. Only the emission fee achieves this feat. The subsidy on the other hand, creates too generous incentives, resulting in excessive amounts of new green generation. Neither version of the TGC scheme is able to replicate the optimal investment profile in new generation capacity. Levels of green generation capacity with a TGC scheme mostly exceed the socially optimal levels.

Nevertheless, they can fall below the optimal level, with increasing rates of technological progress. An explanation could be the damping effect from the percentage requirement on parameters affecting the investment profile with a TGC scheme.

The price of electricity with the emission fee is determined by the (annualized) marginal costs of green electricity generation. In the theoretical model, the price path with the emission fee is monotonically increasing as long as there is no technological progress in green technology. In the presence of technological progress, however, the path is indeterminate. Simulations show that with increasing rates of technological progress, the price path could become strictly concave. Cheaper green technology over time, result in a downward pressure on the price of electricity. With the subsidy, the price of electricity is driven down towards marginal costs of black electricity generation. This results in the lowest price of all the instruments and an excessive demand for electricity. The price path is also invariant to technological progress since it is determined by marginal costs of black electricity generation.

The TGC scheme results in a deviating price pattern compared to the social optimum. The optimality condition for the price is determined by a weighted average of (annualized) marginal costs of green electricity generation and marginal costs of black electricity generation. Although the price path of both versions of the TGC scheme mainly lie below the socially optimal path, this could change with increasing rates of technological progress. Again, the effect of the percentage requirement seems to reduce the effect of technological progress under a TGC scheme. Simulations for the two versions of the percentage requirements also show that the price of electricity is lowest when the requirement is derived from an optimal target share (i.e. the shares calculated from the social optimum). Then, there will be more generation of black electricity, compared to the results for the other version of the percentage requirement. This results in an overall higher level of electricity generation.

With the emission fee, the maximum social surplus is attained. The subsidy on the other hand, cause a loss of social surplus of at least 85 per cent, compared to the social optimum. For the TGC scheme, both versions of the percentage requirement also entail a loss of social surplus. When the requirement is derived from target shares from the social optimum, there is a loss of around 37 to 46 percent, depending on parameter values. Even if the percentage requirement is computed to meet the target path of emission reductions explicitly, there is still a loss of between 22 and 48 per cent.

Results in the paper show that only the emission fee is an optimal policy instrument, given the target set by the regulator. In practice however, an emission fee might not be politically feasible. This was the case in the European Union, where they eventually settled on the EU-ETS. An alternative could be to award a subsidy to green electricity producers to displace polluting black electricity generation. Although this can achieve the target path of emission reductions, it comes at a considerable cost, as well as resulting in excessive use of electricity. Our model does not include a public budget constraint, but a generous subsidy would require considerable means for funding. A costly subsidy could therefore be controversial.

Even though a TGC scheme may be neither the most accurate instrument nor the most cost-efficient, it could prove to be a more politically feasible choice in energy and environmental policy, compared to an emission fee and a subsidy. A TGC scheme is self-contained and a properly derived percentage requirement can attain a specific target path of emission reductions. However, it will not provide accurate incentives for investments in new green replacement generation capacity. There are also costs to consumers over the electricity bill. A TGC scheme is nevertheless likely to have its proponents, to whom regulation without direct involvement from a regulator levying levies taxes and giving subsidies is appealing. In order to achieve a specific target path of emission reductions, the percentage requirement must be calculated in a different manner than commonly used in practice. A TGC scheme where the percentage requirement derived from target shares from the social optimum can only be relied upon to deliver a specific share of green electricity out of total demand for electricity. This turns out to be an inaccurate instrument when the target is a specific path of emission reductions.

6. Appendix

A

In the case where there are no regulations and there is technological progress (ρ > 0), the price of electricity will be decreasing over time. The price decrease results from a decrease in emissions and an increase in green generation capacity, where the latter will dominate.

The optimality condition without regulation reads

A.I. $$p_t = c'(y_t) = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$$

We must have $\dot{p}_t < 0$. In order to prove this, assume that $\dot{p}_t \geq 0$. This leads to a contradiction.

Take the total differentiation of A.I, with respect to time and obtain

A.II. $$\dot{p}_t = c''(y_t)\dot{y}_t$$

With $\dot{p}_t \geq 0.$, then $\dot{y}_t \geq 0$, since $c''(y_t) \geq 0$

A.III. $$\dot{p}_t = -\rho[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + [(r+\rho+\kappa)g'(\bar{z}_t)\dot{\bar{z}}_t + \kappa\bar{z}_t g''(\bar{z}_t)\dot{\bar{z}}_t + \kappa\dot{\bar{z}}_t g'(\bar{z}_t)]e^{-\rho t}$$

If $\dot{p}_t \geq 0$, then from A.III, $\dot{\bar{z}}_t > 0$, since $g'(\bar{z}_t)$ and $g''(\bar{z}_t) > 0$.

However, if $\dot{y}_t \geq 0$ and $\dot{\bar{z}}_t > 0$, then $\dot{p}_t < 0$ which is a contradiction.

Therefore, $\dot{y}_t < 0$, $\dot{\bar{z}}_t > 0$ and $(\dot{y}_t + \dot{\bar{z}}_t) > 0$, resulting in $\dot{p}_t < 0$.

B

In the case where the regulator has set a binding target for emission reductions, the optimality condition states

B.I. $p_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} = \omega_t e^{rt} + c'(\bar{y}_t)$

With depreciation of green generation capacity (κ > 0) and no technological progress for green generation capacity (ρ = 0), we claim that $\dot{p}_t > 0$.

Take the total differentiation of B.I, with respect to time to obtain

B.II. $\dot{p}_t = [(r+\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t) + \kappa g'(\bar{z}_t)]\dot{\bar{z}}_t$

Then, from B.II, sign $\dot{p}_t$ = sign $\dot{\bar{z}}_t$

B.III. $\dot{p}_t = [r\omega_t + \dot{\omega}_t]e^{rt} + c''(\bar{y}_t)c'\dot{\bar{y}}_t$

In accordance with the target set by the regulator, $\dot{\bar{y}}_t < 0$.

In order to obtain a proof through contradiction, assume $\dot{p}_t \leq 0$. This leads to $\dot{\bar{z}}_t \leq 0$. Since $\dot{\bar{y}}_t < 0$, we have $\dot{\bar{y}}_t + \dot{\bar{z}}_t < 0$ and $\dot{p}_t > 0$. This is a contradiction.

Therefore, $\dot{\bar{y}}_t < 0$, $\dot{\bar{z}}_t > 0$ and $\dot{\bar{y}}_t + \dot{\bar{z}}_t < 0$, resulting in $\dot{p}_t > 0$

In the case where there is technological progress for green generation capacity (ρ > 0), $\dot{p}_t$ will be indeterminate.

A total differentiation of B.I with respect to time then provides the following

B.IV. $\dot{p}_t = -\rho[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + [(r+\rho+\kappa)g'(\bar{z}_t)\dot{\bar{z}}_t + \kappa\bar{z}_t g''(\bar{z}_t)\dot{\bar{z}}_t + \kappa\dot{\bar{z}}_t g'(\bar{z}_t)]e^{-\rho t}$

Now the equality sign $\dot{p}_t$ = sign $\dot{\bar{z}}_t$ no longer holds with certainty. As a result, $\dot{p}_t$ is indeterminate.

C

The last term from 30) may be expressed as

$$D = \frac{(1-\alpha_t)\kappa\bar{z}_t\left[\begin{array}{c}\left(\frac{\partial p_t}{\partial x_t}-\alpha_t(r+2\rho+2\kappa)g'(\bar{z}_t)e^{-\rho t}-\alpha_t\kappa\bar{z}_t g''(\bar{z}_t)e^{-\rho t}\right)\left(\frac{\partial p_t}{\partial x_t}-\alpha_t^2[(r+\rho+2\kappa)g'(\bar{z}_t)+\kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t}-(1-\alpha_t)^2c''(y_t)\right)\\ -(1-\alpha_t)\alpha_t\rho g'(\bar{z}_t)e^{-\rho t}\left((1-\alpha_t)c''(y_t)-\frac{\partial p_t}{\partial x_t}\right)\end{array}\right]}{\left(\frac{\partial p_t}{\partial x_t}-\alpha_t[(r+\rho+2\kappa)g'(\bar{z}_t)+\kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t}\right)(1-\alpha_t)\left[\frac{\partial p_t}{\partial x_t}-\alpha_t^2[(r+\rho+2\kappa)g'(\bar{z}_t)+\kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t}-(1-\alpha_t)^2c''(y_t)\right]}$$

D

We apply the following function forms for the demand and cost functions in the numerical model and for the calculations for social surplus

$$P(x_t) = a - bx_t$$

$$c(y_t) = \frac{1}{2}{y_t}^2$$

$$g(\bar{z}_t)e^{-\rho t} = \left(\frac{m{\bar{z}_t}^2}{2} + n\bar{z}_t\right)e^{-\rho t}$$

a, b, m and n are all strictly positive constants and take the following values:
a: 340, b: 20, m: 57, and n: 47.

E

Calculations for social surplus presented in table 4 are derived from the following equations

Emission fee

The optimization for electricity generators with an emission fee is

$$\max \int_0^T [p_t x_t - c(y_t) - \tau_t y_t - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

Social surplus can then be expressed as

$$W^{\tau} = \int_{0}^{\mathrm{T}} [\mathrm{p}(x_t^{\tau})x_t^{\tau} - \mathrm{c}(\bar{\mathrm{y}}_{\mathrm{t}}) - \tau_t \bar{\mathrm{y}}_{\mathrm{t}} - \mathrm{g}(\bar{z}_t^{\tau})e^{-\rho t}k^{\tau}{}_t]\mathrm{e}^{-\mathrm{rt}} + l^{\tau}$$

The symbol $l^{\tau}$is an expression of the lump sum value of the total emission fee in the period. This is given by $l^{\tau} = \int_0^T \tau_t \bar{\mathrm{y}}_{\mathrm{t}} e^{-rt}$. This amount has been extracted from the electricity sector and we must therefore add this when calculating the social surplus using the emission fee.

Subsidy

If the regulator chooses subsidies as the preferred instrument, the electricity generators maximize

$$\max \int_{0}^{T} [p_t x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + \sigma_t \bar{z}_t]e^{-rt}$$

This leads to the following expression for the social surplus

$$W^{\sigma} = \int_{0}^{T} [\mathrm{p}(x_t^{\sigma})x_t^{\sigma} - c(\bar{\mathrm{y}}_{\mathrm{t}}) - g(\bar{z}_t^{\sigma})e^{-\rho t}k_t^{\sigma} + \sigma_t(\bar{z}_t^{\sigma})]e^{-rt} - l^{\sigma}$$

The symbol l^{σ} is an expression for the total present value of the subsidy over the period, given by $l^{\sigma} = \int_0^T \sigma_t \bar{\mathrm{y}}_{\mathrm{t}} e^{-rt}$. This sum comes from outside the electricity sector. In order to calculate the social surplus we must therefore subtract this amount when using subsidies.

Tradable green certificates (TGC)

With a TGC scheme, electricity generators maximize

$$\max \int_{0}^{T} [(p_t - \alpha_t s_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + s_t \bar{z}_t]e^{-rt}$$

The corresponding expression for the social surplus is then

$$W^{TGC} = \int_0^T [q_t^{TGC} y_t^{TGC} + (q_t^{TGC} + s_t^{TGC})\bar{z}_t^{TGC} - c(y_t^{TGC}) - g(\bar{z}_t^{TGC}) e^{-\rho t} k_t^{TGC}] e^{-rt}$$

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Department of Economics
University of Bergen
PO BOX 7802
5020 Bergen
Visitor address: Fosswinckels gate 14
Phone: +47 5558 9200
www.uib.no/econ/