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Simultaneous Use of Black, Green, and White Certificate Systems

Eirik S. Amundsen and Torstein Bye***

ABSTRACT

We formulate a long run model with black, green and white certificate markets that function in conjunction with an electricity market. The markets function well together in the sense that a common equilibrium solution exists, where all targets are satisfied (e.g., the share of green electricity and share of energy saving/ efficiency increase). The equilibrium solution adapts to changing targets but it is, in general, impossible to tell whether this will lead to more, less, or unchanged consumption of "black," "green" or "white" electricity. Hence, if the long run target is to expand the capacity of green electricity generation and energy savings to certain given levels, then these markets may not be the best to use. To obtain clear results, specific parameter values and functional forms are needed. An example based on Norwegian data is provided. In addition, gains and losses in terms of consumers' and producers' surpluses are calculated.

Keywords: renewable energy, electricity, Green Certificates, White Certificates

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1. INTRODUCTION

Many countries have set targets on greenhouse gas emissions, the share of renewables and the share of energy saving (energy efficiency). For these purposes, various market-based mechanisms have been proposed and implemented. In addition to the well-established emissions permit systems ("black" certificates) designed to curb greenhouse gas emissions, so-called "green" and "white" certificate systems have also been initiated.[1] Green certificate systems are designed to meet the target on renewables, while white certificates are intended for achieving the energy savings target. Energy savings is to be understood as additionally generated savings compared with what would otherwise occur due to increasing energy prices.[2] The main objective of this paper is to investigate the compatibility of these certificate systems as they act in concert.

1. The EU "black" certificate system (EU ETS) is the most developed system for carbon emissions and has been in existence since 2005. Green certificate systems are in use in several countries, e.g., the UK ("Renewable Obligation Certificates", Norway and Sweden ("elsertifikater") and the US ("Renewable Portfolio Standards"), while white certificate systems may be found in France ("Certificates d'Economie d'Eenergie"), Italy ("Titoli di Efficienza Energetica"), the UK ("Energy Efficiency Commitment") and the US (Connecticut, Pennsylvania, Nevada)("Energy Efficiency Portfolio Standards). In addition,, several countries have a black, a green and a white certificate system, e.g., the UK, Italy, and Poland.

2. The EU target on energy savings/ energy efficiency increase is formulated as a 20 percent reduction of energy use in 2020 compared with what it otherwise would have been in 2020. http://ec.europa.eu/energy/en/topics/energy-efficiency/

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Black, green and white certificates have in common a process by which the price of the certificate is determined in an interaction between supply and demand in a market. However, unlike a black certificate system that is designed to tax firms for their greenhouse gas emissions, the green and white certificate systems involve both indirect taxes and subsidies endogenously determined in the market. Producers of renewable energy and generators of energy saving activities receive a subsidy in terms of marketable certificates (supplied free of charge) while the purchasers of electricity and the receivers of energy saving improvements (end-users/ retailers of energy) are paying a tax in terms of obligatory purchases of certificates. Hence, the green and white certificate systems are self-contained in the sense that taxation and subsidization occurs within the energy market itself without involving the government directly in terms of revenues (contrary to the case of the black certificate system).

The stated motivations for adopting such systems are many and range from the regulation of market failures to environmental preservation, job creation and innovation with a consideration for distributional equity and political feasibility (Goulder and Parry, 2008; Fischer and Preonas, 2010). In particular, the three certificate systems may be related to proper market failures such as climate change (a negative externality), security of supply (comprising aspects of a public good, see Joskow, 2008) and energy efficiency gaps (partly due to lack of the public good: information, see Jaffe and Stavins, 1994). Hence, the adoption of these systems may be seen as attempts to correct for market failures where the cost of this is levied on the producers of fossil energy and end users of energy. The point is that the marginal private cost of fossil energy generation should be raised to reflect the marginal social cost by adding a marginal externality cost and that the generation of public goods should be stimulated to a level above what would otherwise occur if left to the private sectors alone. The ability of these systems to cost-effectively account for market failures of the above mentioned types will be discussed later. Along with this the relevance and efficiency of some of the goals and sub-goals will be discussed and questioned. Still such goals are imbedded in the legislation in many economies (e.g. within the EU/EEA), wherefore analyses of which instruments best achieve these goals are relevant, even though some of the goals and targets may be considered inefficient from an economic point of view.

There exists an abundant literature on the functioning of black certificate systems (see, e.g., Ellerman, 2010). In addition, a sizable literature on green certificate system has emerged, whereas the literature on white certificates is somewhat more limited (Mundaca and Neij, 2006; Pavan, 2008; Child et al., 2008; Sorrel et al., 2009; Wirl, 2015; Giraudet and Finon, 2015). Some of the literature addresses the interplay between the green certificate market and the electricity market (e.g., Bye, 2003; Nese, 2003; Amundsen, Baldursson and Mortensen, 2006; Fischer, 2009; Fischer and Preonas, 2010), while some consider the electricity market, the black certificate market and the green certificate market (e.g., Amundsen and Mortensen, 2001, 2002; Unger and Ahlgren, 2005; Böhringer and Rosendahl, 2010). Recently, some literature has emerged addressing all certificate systems taken together (Meran and Wittmann, 2012).

Considering each by itself, all certificate systems may, under given conditions, achieve the targets they are designed for, but as the targets for renewables and energy savings typically are set in percentages, one cannot immediately conclude anything about the quantities of renewables or energy savings resulting from, say, harsher targets. For instance, it has been shown that an increase in the required share of green electricity may result in less green electricity due to price effects in the electricity market (Amundsen and Mortensen, 2001). However, the opposite may also be true,

energy-efficiency-directive

and harsher targets of renewables may even lead to increasing electricity consumption (Bye, 2003; Fischer, 2009).

In addition to this, further complications arise when several systems are in use at the same time. For instance, Amundsen and Mortensen (2001) show that a higher price on black certificates leads to less green electricity generation when using a green certificate system, while Böhringer and Rosendahl (2010)) show that a green certificate system on top of a black certificate system serves the dirtiest power technologies compared with a black certificate system alone. This result is also supported by Fischer and Preonas (2010) in their analysis. Along the same lines, Meran and Wittmann (2012) show that demand side management (e.g., using a white certificate system) achieves its underlying goal of an increase in end-users' energy efficiency solely at the expense of a reduced environmental efficiency of energy production. Clearly, adding a white certificate system on top of the black and green certificate systems further complicates matters. Inherently, there may be a conflict, e.g., if a green certificate system stimulates electricity demand, then it may run counter to the intension of the white certificate system, i.e., to stimulate energy saving/ energy efficiency.

In this paper, we investigated the interplay and compatibility of the three certificate systems further as they work jointly in an electricity market. The motivation for this investigation is that additional white certificate systems have actually been adopted or are planned to be used in several countries. Hence, it should be of interest to investigate whether these systems are at least compatible in theory when considering all markets at the same time.

Compared with the existing literature, e.g., Böhringer and Rosendahl (2010), Fischer and Preonas (2010), and Meran and Wittmann (2012), we aimed to further untangle the various effects of partial changes of the strength of the various targets. For instance, we investigate whether a harsher target on green electricity generation leads to more or less energy savings being generated, or whether a harsher target of energy savings leads to more or less green electricity being generated. Likewise, we investigate what effects a harsher target on black electricity reduction has on green and white electricity generation.

To answer questions such as these, we formulate a model and consider equilibrium solutions where the various targets are complied with for any chosen level of the targets. The model applied is a stylized analytical model that ignores complicating effects of lumpiness and Kirchhoff's Voltage Law (KVL) that typically imply underestimation of total costs and lead to distortion of investment incentives and market equilibrium. However, even in such a simplified stylized model the results are, to a large extent, ambiguous when considering the market effects on the various types of electricity products: "green electricity," "black electricity" and "white electricity" (electricity savings) following these systems. Because analytical results are ambiguous, a detailed discussion of partial effects is called for in order to understand how these markets function. In addition, to further elucidate how such markets may function we investigate the systems in a numerical model considering realistic data and parameter values compiled from the Norwegian electricity sector. Clearer results now appear, although some ambiguities remain. Along with this, we also study the distributional effects in terms of consumers' surplus, producers' surplus and social surplus, and ask which party is gaining and which is losing from introducing harsher targets.

2. MODEL

To analyze the interplay between an electricity market, a tradable green certificate (TGC) market and a tradable white certificate (TWC) market, we consider an economic model building on the following assumptions. Electricity producers supply a common wholesale market within which a single wholesale electricity price is established. Electricity generation is based on both fossil fuel ("black electricity") and renewable sources ("green electricity"). In addition to the wholesale price, producers of green electricity obtain one TGC per unit of green electricity delivered. This may be sold on the TGC market. Producers of black electricity obtain only the wholesale price.

Electricity producers/ distributors[3] also provide energy savings ("white electricity") through, e.g., ancillary services, installation of smart devices, and technological improvements, and obtain a price per unit electricity saved valued at the wholesale price. In addition, they obtain one TWC per unit of energy saved, to be sold on the TWC market. Retailers purchase electricity on the wholesale market for delivery to end-users. The retailers are obliged to purchase TGCs on the TGC market, and TWCs on the TWC market corresponding to certain percentage requirements. The electricity is distributed to end users, and a single end-user price is established. End-users are assumed to consider additional electricity savings as equivalent to electricity consumption, i.e., one unit of electricity saved as a result of the TWC system ("white electricity") has the same value as one extra unit of electricity consumed. Hence, an inverse demand function is defined over the sum of the three types of electricity, for short, called "electricity equivalents."

A public authority is assumed to issue TGCs in a one-to-one relationship to the amount of green electricity generated and to set a TGC percentage requirement for the end users/ retailers as a proportion of electricity delivered to end users. In the same way, the public authority is assumed to issue TWCs and to set a percentage requirement for TWC purchases for the end users/ retailers. Hence, both percentage requirements are set according to electricity actually delivered and not according to total consumption of electricity equivalents. In addition, it is assumed that carbon emissions stemming from the generation of black electricity are regulated by a permit system or a tax. To account for this, the price (tax or permit price) of carbon emissions is included in the cost functions of black electricity generation.

It is assumed that perfect competition prevails in all markets, with many producers of electricity (both black, green and white), many retailers, and many end users. Hence, all agents treat the various prices as given by the market.

We apply the following symbols and functional relationships.

x_b = Quantity of electricity generated from fossil sources (black electricity)
x_g = Quantity of electricity generated from non-fossil sources (green electricity)
x_w = Quantity of additional electricity savings (white electricity)
x = Total quantity of electricity equivalents, i.e., $x = x_b + x_g + x_w$
p = Marginal value of consumption of electricity equivalents
p_e = Wholesale price of electricity
p_{gc} =Price of TGCs
p_{wc} = Price of TWCs
α = Percentage requirement for green electricity as a proportion of electricity consumption of black and green electricity, i.e., $x_g = \alpha(x_b + x_g)$
β = Percentage requirement for electricity saving (white electricity) as a proportion of electricity consumption of the sum of black and green electricity, i.e., $x_w = \beta\,(x_b + x_g)$
τ = Parameter representing a carbon emission permit price or a carbon tax ("carbon price")

3. Observe that the white certificate system is a system for promoting energy savings in addition to what would otherwise occur due to, e.g., generally increasing energy prices. It is the producers/ distributors of energy that undertake energy efficiency measures for the final users that are consistent with a pre-defined percentage of their annual energy deliverance (see Pavan 2008; and Giraudet and Finon, 2015).

g^d = Demand of TGCs
g^s = Supply of TGCs
w^d = Demand of TWCs
w^s = Supply of TWCs
$p(x)$ = Inverse demand function of electricity equivalents, where $(\partial p(x)/\partial x) = p' < 0$
$C_b(x_b, \tau)$ = Industry cost function[4] for black electricity with fossil emission constraints, where $(\partial C_b/\partial x_b) = C_b^{'} > 0$, $(\partial^2 C_b/\partial x_b^2) = C_b^{"} \geq 0$, $(\partial C_e/\partial \tau) = C_\tau^{'} > 0$ and $(\partial^2 C_b/\partial x_b \partial \tau) = C_{x_e\tau}^{"} > 0$[5]
$C_g(x_g)$ = Industry cost function for green electricity, where $(\partial C_g/\partial x_g) = C_g^{'} > 0$, $(\partial^2 C_g/\partial x_g^2) = C_g^{"} > 0$[6]
$C_w(x_w)$ = Industry cost function for white electricity, where $(\partial C_w/\partial x_w) = C_e^{'} > 0$, $(\partial^2 C_w/\partial x_w^2) = C_w^{"} > 0$[7]

In aggregate, producers maximize profit:

$$\Pi(x_b, x_g, x_w) = p_e x_b + [p_e + p_{gc}]x_g + [p_e + p_{wc}]x_w - C_b(x_b, \tau) - C_g(x_g) - C_w(x_w)$$

The first-order conditions for black, green and white electricity generation, respectively, are

$$p_e = C_b^{'},\; p_e + p_{gc} = C_g^{'},\; p_e + p_{wc} = C_w^{'} \qquad (1)$$

i.e., the seller price (wholesale price plus certificate price) equals the marginal cost for each of the electricity equivalents.

For each unit of electricity equivalents delivered to end users, retailers must pay the wholesale price plus a share equal to $(\alpha/1+\beta)$ of the TGC price as well as a share equal to $(\beta/1+\beta)$ of the TWC price. For simplicity, electricity distribution is assumed costless. With a large number of retailers, the competitive equilibrium established by the market must be characterized by a consumer price equal to a weighted average of the wholesale price and the certificate prices: $p(x) = p_e + (\alpha/(1+\beta))p_{gc} + (\beta/(1+\beta))p_{wc}$. Otherwise, we assume that both the amount of TGCs

4. The industry cost function is derived by “horizontal summation” of the individual cost functions, i.e., the cost of aggregate market supply is minimized. Using the industry cost function avoids using messy notation to describe individual decisions. Our prime interest is in the equilibrium market solution, not individual decisions. Little information should be lost by this approach as individual first-order conditions for electricity producers correspond directly to those derived in the analysis.

5. The cost function for black electricity conditional on an emission permit price or an emission tax may be derived from a standard cost minimization problem, with the additional constraint that a permit price or a tax will have to be paid per unit of carbon emitted.

6. Black and green marginal costs are to be understood as long run marginal costs. These include both short run operational cost as well as long run capital costs. For many renewable technologies the short run marginal costs may be close to zero (e.g. wind power generation). However, the long run marginal costs may be sizable even for such renewable technologies. In principle the long run marginal costs should include the full cost of expanding the capacity for electricity provision including possible reinforcements of transmission capacity. Particular features relate to economies of scale and lumpiness in transmission expansion as well as to effects of the Kirchhoff’s Voltage Law (see e.g. Turvey, 2000; Smeers, 2005; Joskow and Tirol, 2005; Hirt, 2015). These features may affect the marginal costs of increasing the percentage requirements (see Munoz, Sauma and Hobbs, 2013). As already noted transmission lumpiness and Kirchhoff’s Voltage Law are not included in our model, but possible consequences are commented on in the numerical model for the Norwegian example to follow.

7. Black electricity plants (e.g., coal fired plants) may well be replicated at constant cost whereas green electricity generation from wind power typically is restricted by Nature’s varying supply of good sites for windmills. White electricity is presumably also becoming increasingly costly at the margin as electricity savings are increased. Hence, contrary to the generation of black electricity, we only consider increasing marginal costs for green electricity generation and for white electricity and not constant marginal cost cases.

and TWCs are measured in the same unit as green and white electricity, respectively. Thus, the demand for TGCs is given by $g^d = \alpha(x_b + x_g)$ and the supply by $g^s = x_g$. Likewise, the demand for TWCs is given by $w^d = \beta(x_b + x_g)$ and the supply by $w^s = x_w$.

In equilibrium, the following conditions must be satisfied in addition to 1):

$$x = x_b + x_g + x_w \tag{2}$$

$$x_g = \alpha(x_b + x_g) \tag{3}$$

$$x_w = \beta(x_b + x_g) \tag{4}$$

$$p(x) = p_e + (\alpha/(1+\beta))p_{gc} + (\beta/(1+\beta))p_{wc} \tag{5}$$

Observe that the TGC and TWC systems imply that the revenues obtained from sales of certificates exactly correspond to the subsidies received by the producers of green electricity and the producers of white electricity. End users pay $(\alpha/1+\beta)p_{gc}x$ and $(\beta/1+\beta)p_{wc}x$, for TGCs and TWCs, respectively; while the producers of green electricity receive $p_{gc}x_g$, and the producers of white electricity receive $p_{wc}x_w$. To see that these sums are pairwise identical, note from 1), 2), and 3) that $x_g = (\alpha/(1+\beta))x$ and that $x_w = (\beta/(1+\beta))x$.

Furthermore, by substituting 5) into 4), one may observe that

$$p(x) = \left(1 - \frac{\alpha}{1+\beta} - \frac{\beta}{1+\beta}\right)C_b^{'}(x_b,\tau) + \frac{\alpha}{1+\beta}C_g^{'}(x_g) + \frac{\beta}{1+\beta}C_w^{'}(x_w) \tag{6}$$

i.e., in equilibrium, the marginal willingness to pay for electricity equivalents is equal to a linear (or convex) combination of marginal generation costs with the adjusted percentage requirements as weights.

3. RESULTS

Total differentials with respect to the certificate shares α and β, and of τ show that the effects in general depend on all the supply elasticities, the demand elasticity and the parameters, α, β and τ as reported in Appendix A. A summary of the impact of these parameters on the relevant variables is shown in Table 1. Results in the table show

that a TGC system and a TWC system achieve their objectives, namely, to increase the share of green electricity and to increase the share of electricity savings (white electricity) out of total electricity consumption, respectively. However, as the targets are formulated in terms of percentages, one cannot immediately draw any conclusions with respect to the effects on quantities of green and white electricity generated of introducing such instruments.

In particular, Table 1 shows that an increase in the percentage requirement for green electricity, α, does not necessarily lead to increased generation of green electricity[8], nor does an increased percentage requirement for white electricity, β necessarily lead to more electricity savings. Hence, if the increase of the percentage requirement of green electricity leads to a reduced demand for electricity, the generation of green electricity may decrease and still satisfy the increased percentage requirement provided that the percentage reduction of green electricity is less than the percentage reduction of electricity consumption. Likewise, for an increase of the percentage requirement of white electricity, savings may actually decrease if electricity demand decreases. The only clear result on quantity effects from introducing a TGC system and a TWC system is that the generation of black electricity definitely will decrease when increasing the percentage requirement for green electricity.

8. This result carries over from the simpler model in Amundsen and Mortensen (2001).

Table 1: Effects of increasing values of α, β and τ: General case

	x	x_b	x_g	x_w	$x_b + x_g$
α	?	< 0	?	?	?
β	?	?	?	?	?
τ	< 0	< 0	< 0	< 0	< 0

Table 2: Effects of increasing values of α , β, and τ: Special cases for which signs can be determined

	x	x_b	x_g	x_w	$x_b + x_g$
α	$< 0 \; if \; C_b^{''} = 0$	< 0		$< 0 \; if \; C_b^{''} = 0$	$< 0 \; if \; C_b^{''} = 0$
α	$> 0 \; at \; \alpha = 0$		$> 0 \; at \; \alpha = 0$	$> 0 \; at \; \alpha = 0$	$< 0 \; at \; \alpha = 0$
β	$> 0 \; at \; \beta = 0$	$< 0 \; if \; \alpha = 0$	$< 0 \; if \; \alpha = 0$	$> 0 \; at \; \beta = 0$	$< 0 \; if \; \alpha = 0$
τ	< 0	< 0	< 0	< 0	< 0

In addition to this, the analysis shows that an increase in the carbon price will lead to a reduction of the generation of black electricity when interacting with TGC and TWC systems. However, it will also lead to a reduction of green electricity generation and of electricity savings, which may be seen as unwanted side effects of the carbon price increase. These results are due to the design of the TGC and TWC systems. In particular, from 6), we see that the end user price of electricity equivalents in equilibrium should be equal to a marginal cost composed as a linear combination of the marginal costs of generating the various types of electricity in the correct proportions. As the carbon price increases, it merely shifts the weighted marginal cost curve upwards and creates a higher end user price of electricity. This leads to less consumption of electricity equivalents and a unilaterally reduction of all types of electricity, as these are set in fixed proportions.

Other compatibility effects may be seen from Table 2, which summarizes various special cases. For instance, one may observe that an increase in the percentage requirement for electricity savings, β, will lead to less generation of both black electricity and green electricity if there is no TGC market (i.e., if $\alpha = 0$). Furthermore, one may observe from Table 2 that there may be a stimulating effect from introducing a TGC market with small values of the percentage requirement. Hence, evaluated at $\alpha = 0$, introduction of a TGC system will increase the generation of electricity and the generation of both green and white electricity, separately. However, it will not stimulate the sum of black and green electricity. Similarly, one may observe from Table 2 that there may be stimulating effects from introducing a TWC system with small values of the percentage requirement. Hence, evaluated at $\beta = 0$, a TWC system will increase the generation of electricity equivalents and white electricity, in particular.

An important theoretical result of this analysis (see Table 2) is that the total demand for electricity equivalents may actually increase as a result of increased percentage requirements and lead to a lower wholesale price of electricity. This is important for tax incidence and for the question of who is really paying for the extra costs of increasing shares of green electricity and additional electricity savings[9]. This is not only a theoretical problem but also the case of a real world setting. To investigate further how certificates markets function when they are simultaneously active, we con-

9. A similar observation was made in Bye (2003) studying the relationship between the electricity market and a single green certificates market. A numerical model calibrated on 2003 data from the Norwegian electricity market showed that electricity consumption could actually increase as the percentage requirement increases.

struct a numerical model considering all three certificate markets and the new concept of electricity equivalents (i.e., including electricity savings). The model is calibrated on data for the Norwegian electricity market for the year 2016.

5. A CALIBRATED MODEL

In formulating and calibrating the numerical model for the markets involved, it is convenient to consider the dual version of the analytical model presented earlier. Hence, demand and supply functions are formulated using a Cobb Douglas structure with relevant demand and supply elasticities (see Appendix B).

In short, we consider a demand function for electricity equivalents, $f(p)$, defined by

$$x = f(p), \text{ where } p = p_e + (\alpha/(1+\beta))p_{gc} + (\beta/(1+\beta))p_{wc}$$

In addition, we consider supply functions for the various electricity products; black electricity, $h(p_e)$, green electricity, $g(p_e+p_{gc})$, and white electricity, $u(p_e+p_{wc})$. As these are set to constitute specific proportions of total electricity provision, we have

$$\frac{(1-\alpha)}{(1+\beta)} f(p) = h(p_e) = x_b$$

$$\frac{\alpha}{(1+\beta)} f(p) = g(p_e + p_{gc}) = x_g$$

$$\frac{\beta}{(1+\beta)} f(p) = u(p_e + p_{wc}) = x_w$$

The equilibrium of the model is, thus, given by $x=x_b+x_g+x_w$.

We apply market data and elasticities for the Norwegian electricity market to calibrate the model (See Appendix B).

First, we investigate the effects on the various electricity components of increasing the percentage requirement for green electricity while keeping the percentage requirement for white electricity fixed at a given level, i.e., $\beta = 0.2$**.** Second, we investigate the effects on the various electricity components of increasing the percentage requirement for white electricity while keeping the percentage requirement for green electricity fixed at a given level, i.e., $\alpha = 0.2$. Third, we investigate the effects on the various electricity components of increasing the percentage requirement for both green and white electricity simultaneously. Fourth, we investigate the effects of increasing the CO_2 tax, and fifth, we investigate the effects of increasing the CO_2 tax when there are no markets for green and white certificates.

As is seen from Figure 1, increasing the percentage requirement for green certificates while keeping β=0.2 will lead to reductions of the generation of both white and black electricity, while the generation of green electricity will increase.[10] Furthermore, the consumption of total electricity

10. Referring to Munoz, Sauma and Hobbs (2013) the marginal cost of increasing the percentage requirement α may well fall as the expansion of green generation capacity can induce lumpy transmission reinforcements. Likewise the functioning of Kirchhoff's Voltage Law may also affect the marginal costs. Such effects are not taken account of in the model. However, this is probably not a problem for Norway. Looking at the capacity expansion of green electricity generation triggered by the existing TGC system that has taken place in Norway up until now, it turns out that a dominant part (85 to 90%) of the expansion of green generation capacity has manifested itself in the form of a large number of small scale water power plants that are rather scattered

Figure 1: Generation and consumption of black, green and white electricity with increasing α while keeping β=0.2

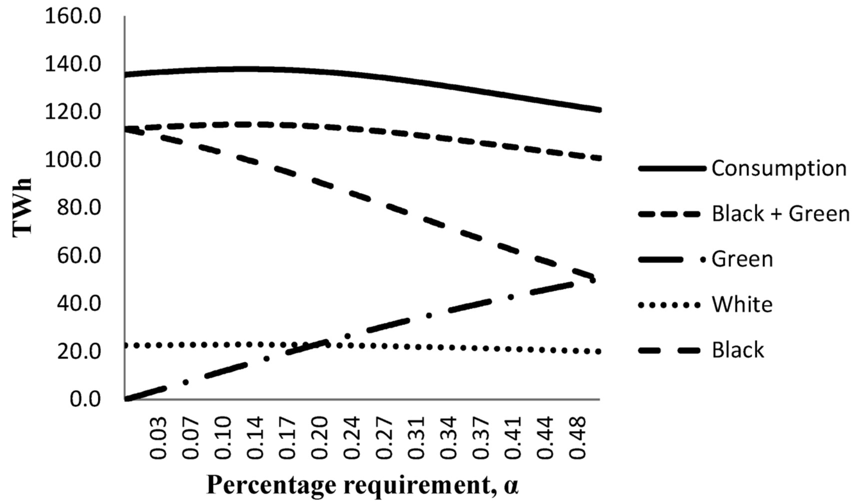
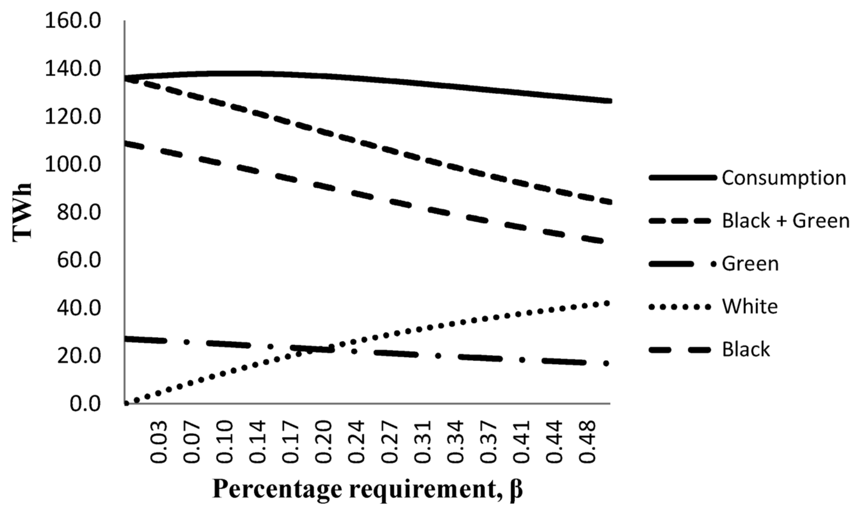


Figure 2: Generation and consumption of black, green and white electricity with increasing β while keeping α=0.2



equivalents will first increase, thereafter reach a maximum, and then decrease.[11] This is also the case for the “non-virtual” electricity generated (sum of green and black electricity); at first it increases, thereafter reaches a maximum, and then decreases.

Likewise, as seen from Figure 2, an increase in the percentage requirement for white certificates while keeping α=0.2 will lead to reductions of the generation of both green and black electric-

across the country (see NVE-Energimyndigheten, 2016, page 20). Hence, reinforcements of networks have not been sizable and lumpy and could best be described by the Continuous Transportation model discussed in Munoz, Sauma and Hobbs (2013) that will not cause problems of the above mentioned kind. Up until 2020 (the target year for the analysis) this development will probably continue. The potential expensive large scale offshore wind power farms that may give rise to lumpiness in transmission are not viable for years to come due to low expected future electricity prices within Nord Pool.

11. For similar results see also Fischer (2009) and Felder (2011).

Figure 3: Generation and consumption of black, green and white electricity with simultaneous increase of α and β

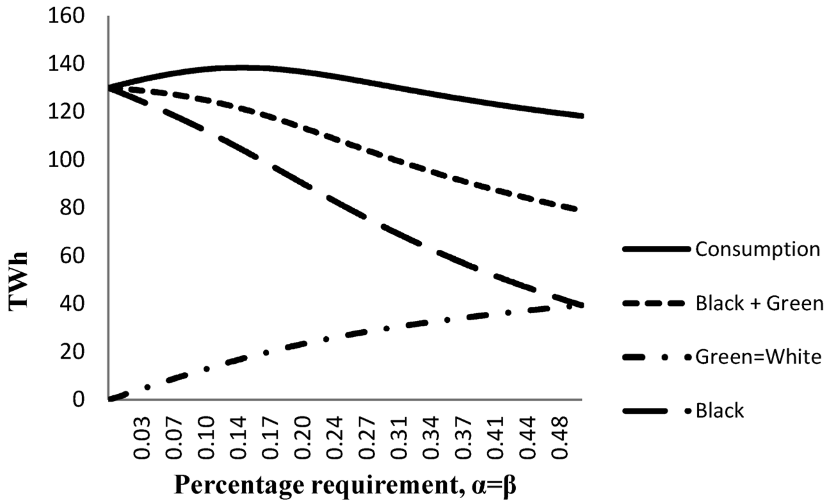
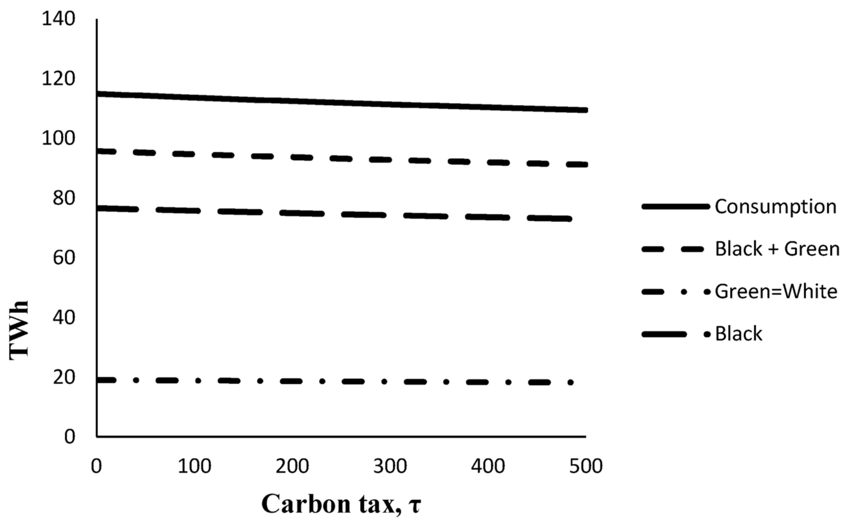


Figure 4: Generation and consumption of black, green and white electricity with increasing carbon tax τ, including certificates markets with α=β=0.2



ity, while the generation of white electricity will increase. In addition, for this case, the consumption of total electricity equivalents (including white electricity) will first increase, thereafter reach a maximum and then decrease as the percentage requirement for white certificates increases.

Figure 3 shows that a simultaneous expansion of the percentage requirements for both green and white certificates results in increases in both green and white electricity (curves covering each other) whereas black electricity and the sum of green and black electricity decreases. Furthermore, the consumption of total electricity equivalents will first increase, reach a maximum and then decreases.

As already noted and shown analytically in Appendix A, an increase in the CO_2 tax leads to a unilateral reduction of all types of electricity generation and of the total consumption of electricity equivalents (See Figure 4). In particular, this means that both green and white electricity generation

Figure 5: Generation and consumption of black, green and white electricity with increasing carbon tax τ and no certificates markets

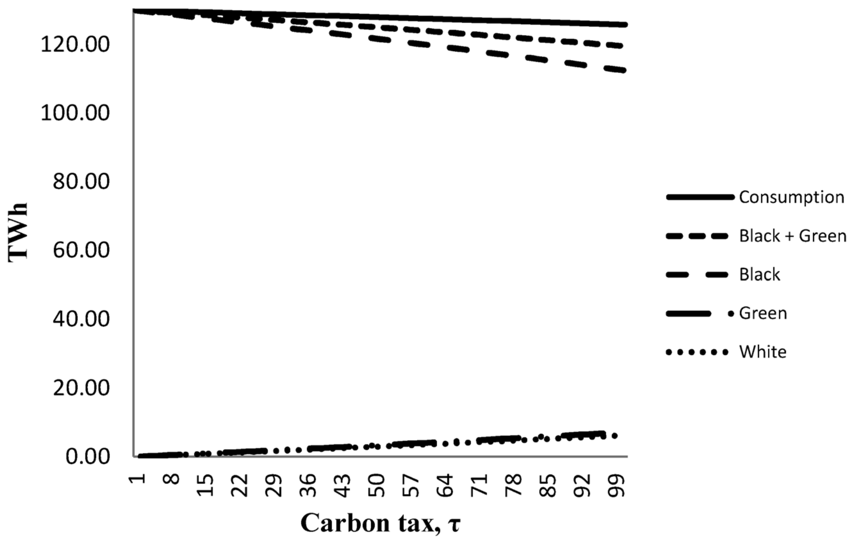


Table 3: Effects of increasing values of α, β and τ: Numerical model

	x	x_b	x_g	x_w	$x_b + x_g$
$\alpha(\beta=0.2)$	? (i)	< 0	> 0	< 0	? (iv)
$\beta(\alpha=0.2)$	? (ii)	< 0	< 0	> 0	< 0
$\alpha=\beta$	? (iii)	< 0	> 0	> 0	< 0
$\tau(\alpha=\beta=0.2)$	< 0	< 0	< 0	< 0	< 0
$\tau(\alpha=\beta=0)$	< 0	< 0	> 0	> 0	< 0

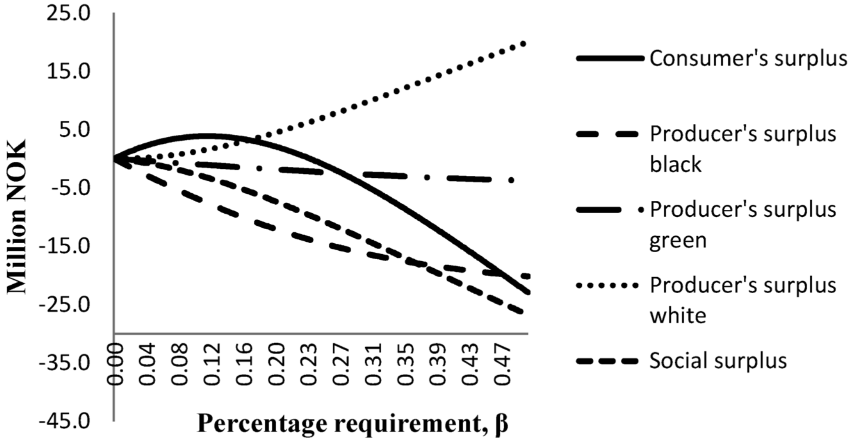
are actually reduced as the CO_2 tax increases. These effects may be seen as unwanted side effects of the green and white certificates markets.

Considering instead the case where there are no certificates markets, an increase in the CO_2 tax would lead to not only a reduction in the generation of black electricity but also an *increase* in green and white electricity. Thus, the unwanted effects from the above case are avoided, as is illustrated in Figure 5. The figure also illustrates that both the total consumption of electricity equivalents and the sum of black and green electricity generation decrease as the CO_2 tax increases.

The results of this section thus far are summed up in Table 3. For the cases denoted (i), (ii), and (iii), total consumption of electricity equivalents, x, first increases, reaches a maximum at $\alpha=0.128$, $\beta=0.113$ and $\alpha=\beta=0.141$, respectively, and then decreases. For the case denoted (iv), the sum of green and black electricity shows a similar development for increasing values of α. The sum reaches a maximum at $\alpha=0.129$.

For all cases of increases of α and β considered, the end user price of electricity equivalents at first decreases, thereafter reaches a minimum and then increases. Corresponding to this, there are changes of the various types of surpluses; i.e., consumer's surplus, producer's surplus, tax revenue and total social surplus (the sum of the surpluses). For all cases considered, the social surplus decreases. However, it should be noted that the benefit of greenhouse gas reductions stemming from

Figure 6: Change in welfare components due to harsher targets of energy savings/ efficiency



the various policies has not been included, so one cannot draw the immediate conclusion that the adopted policies are welfare worsening.[12]

In addition to this, it may be interesting to note that the consumers' surplus actually increases for increasing values of α and β before it starts to decrease again. The loser in this setting is the producer of black electricity, in particular. Hence, producers' surplus for the producers of black electricity is mostly transferred to consumers' surplus. Additionally, the producer's surpluses for green and white electricity may increase, as they are stimulated by increasing percentage requirements. For instance, the producer's surplus of white electricity generation is increasing for increasing values of β as α is kept constant, while the producers' surplus for green electricity is decreasing (see Figure 6). A parallel result appears if α is increasing and β is kept constant. If both α and β are increasing, then both producer's surpluses increase.

6. DISCUSSION

To evaluate policy instruments such as the black, green and white certificate systems, it is important to understand how these specific instruments interact with each other and under what conditions multiple policy instruments are necessary (Fischer and Preonas, 2010). In addition, the assessment of such instruments must be related to the motivations and goals of adopting them.

There are different levels of interpretation of what the goals of the adopted instruments really are. In the cases considered here, an immediate and direct way of interpreting the goals is simply to take the stated goals at their face values, i.e., that the goals are to achieve a reduction of the generation of black electricity and to attain specific percentage levels of renewables and energy savings. If this is the case, then the three systems work reasonably well. They do induce a reduction in black electricity, and they do attain the percentage targets.

However, underlying the stated percentage targets, there must be some more comprehensible goals from which they are derived. These could, for example, be a goal to increase the size of

12. For Norway, however, we are very close to being able to draw such a conclusion. The reason is that the Norwegian electricity generation is based on almost 100% hydropower, and only small hydro power plants are considered green in the Norwegian-Swedish green certificates market. The remainder of the older large hydropower plants in Norway and Sweden do not qualify for green certificates and are, therefore, considered "black" in the terminology of the model. This stands in contrast to what would be the case in thermal-based power producing countries such as Denmark and Germany.

the generation capacity of green electricity and to increase the amount of electricity savings (i.e., in quantitative terms rather than in percentage terms). The specific percentage targets chosen can then be seen as a step on the way to achieving these underlying quantitative goals as in the Norwegian-Swedish TGC market. [13] Viewed in this way, the green and white certificate systems are no longer so advantageous. As has been shown in this article, it is generally not possible to tell whether introduction of a TGC and a TWC market on top of an electricity market will lead to more generation capacity of green electricity and electricity savings. Hence, if the long run target is to expand the capacity of green electricity generation and increase the amount of electricity savings to certain given levels, then these markets may not be the best to use. With such targets direct subsidies (i.e. feed-in tariffs) may be more efficient instruments to apply.

Things are, however, different for the black certificates system. This system does promote the goal of reducing the generation of black electricity in a cost effective way. It is a robust conclusion in the paper that an increase of the black certificate price (carbon price) leads to a reduction of black electricity generation. Unfortunately, - when a TGC and a TWC system are active at the same time—the black certificate market also reduces the generation of green and white electricity (see Table 3). This would not have been the case if green and white electricity generation instead were stimulated by direct subsidies such as feed-in tariffs.

However, beyond the goals to reduce the generation of black electricity, to increase the generation of green electricity and to increase electricity savings, there exist more profound motivations and goals for the society that explain why society wants to regulate them. Looking at this from a purely economic point of view[14] the regulation of market failures stand out as particularly important, and along with this, the choice of cost minimizing instruments when facing uncertainty. Hence, existence of several different and specific market failures involved in electricity generation may constitute reasons for announcing several separate goals and for applying several instruments. In addition to this the existence of uncertainty may itself be an economic argument for combining instruments even though there may be only one single market failure to address.

However, it is not at all obvious which particular and specific market failure each of the percentage goals of green and white electricity is intended for.[15] Things are, of course, different for the goal on emission reduction of greenhouse gases. Use of fossil energy constitutes an important market failure in terms of the negative externality of climate change. Nevertheless, one could see the three certificates systems as instruments for achieving the single goal of reducing the emissions of greenhouse gases (see e.g. Marcantonini and Ellerman, 2015). However, if this is the only and

13. In the Norwegian-Swedish TGC market the intension is to jointly increase the capacity of green electricity by 28.4 TWh by 2020. In order to achieve this it is necessary to adjust the percentage requirements along with adjustments following from revealed uncertainties. Hence, it is not the percentage as such that constitute the goal but rather the quantitative expansion of capacity.

14. As pointed out by Weitzman (1974) and other economists (e.g. Goulder and Parry, 2008; Fischer and Preonas, 2010), there may be a host of other reasons than purely economic reasons that explain why a particular economic activity is regulated and why particular instruments are chosen. These are outside of the scope of this paper and we will not go into a discussion of these here.

15. Generation and use of electricity may involve several other aspects of market failure that are not directly addressed by the instruments under consideration in this paper. These include information and energy efficiency gaps (see e.g. Weitzman, 1974; Jaffe and Stavins, 1994; Fillipini et al., 2014), security of supply (see e.g. Joskow and Tirol, 2007; Joskow, 2008; Newbery, 2015; Newbery and Grubb, 2015), induced technological change and spill-over effects (see e.g. Popp, 2002; Newell, Jaffe and Stavins, 1999). Furthermore, there is a large body of theoretical and empirical literature considering instruments and governance measures to release spill-over effects on cost reduction from learning- by- doing for the attainment of energy and climate targets (see e.g. Jamasb, 2007; Neuhoff, 2008; Nordhaus, 2014; Bigerna, Bollino and Micheli, 2016; Newbery 2017).

ultimate goal, one may ask why it is necessary to have several instruments and targets to achieve this goal. Clearly, as pointed out by several economists additional specific targets on the share of renewables and energy savings/ efficiency improvements may function as unnecessary and costly constraints (see, e.g., Böhringer and Rosendahl, 2010; Fischer and Preonas, 2010; Giraudet and Finon, 2015).[16] A simple observation is that a carbon tax or a black certificates market itself may generate the preferred effects, i.e., as shown in the article, an increase of the carbon price, when acting alone, will reduce the generation of black electricity, but at the same time, also increase the share of green electricity as well as increase the level of energy savings through price increases (see Figure 5).

Against this, one may claim that combinations of instruments may be a good thing even with a single goal when various types of uncertainty are prevalent. Uncertainty related to the marginal abatement cost function and/ or the marginal social benefit function of abatement implies that the optimal *ex post* abatement is also uncertain. As shown by Weitzman (1974) the choice of whether to use a price mechanism or a quantity mechanism should be governed by which of these that gives the least expected loss in case of assessing the marginal abatement cost wrongly, when basing the *ex ante* decisions on expected values of cost and benefit functions. However, building on Weitzman's seminal paper it has later been shown that the expected *ex post* loss from wrong assessment may be even smaller if quantity and price mechanisms are combined. Indeed, as shown by, e.g., Roberts and Spence (1976) and Kwerel (1977), it may be optimal from the point of view of society to combine a certificate system with an additional price instrument such as floor and ceiling prices (a so-called "hybrid system"). More recently, Pizer (2003), Jacoby and Ellerman (2004), Burtraw and Palmer (2006), Goulder and Parry (2008) showed how a system of "safety valves" (ceiling and floor prices) under uncertainty may increase the efficiency of a dynamic emissions certificate system that allows banking.[17] Relating this to the cases considered in this article, it would seem logical to address uncertainty by adding such safety valves to the black certificate system rather than to add certificate systems of green and white electricity, if reduction in the emissions of greenhouse gases is the single ultimate goal while recognizing uncertainty.

In conclusion, an evaluation of the efficiency of the three certificate systems must depend on the motivations and goals of adopting them. If the goals are accepted as they are without any consideration of the economic efficiency of the goals, then all certificate systems work well. However, if the percentage goals are to attain certain quantitative targets of green and white electricity rather than to attain the given percentages (as is the case in the Norwegian Swedish TGC system), then feed-in tariffs may turn out be more direct and better alternatives to the TGC and the TWC systems. Furthermore, if the instruments are to be judged by the specific economic goals of addressing market failures, then neither the TGC nor the TWC system seem efficient. Hence, only the black certificate system directly addresses a market failure i.e. the negative external effect of greenhouse gas emission. Furthermore, the TGC and the TWC systems do not seem to add to the efficiency in achieving the greenhouse gas targets when recognizing the importance of uncertain abatement costs.

16. On this specific point, Fischer and Preonas (2010) state: "... once emissions from electricity generation are sufficiently priced or capped, additional renewable energy policies lead to little further emissions reductions or environmental benefit; in fact, they lower costs for the dirtier producers." Along the same lines Giraudet and Finon (2015) write: "In all countries (i.e., France, Italy, and the UK), white certificate obligations coexist with the EU CO_2 Emissions Trading System. The latter can be seen as a first-best solution to reduce CO_2 emissions. Standard microeconomic reasoning predicts that the combination of two instruments will reduce CO_2 emissions less cost-effectively than the stand alone first-best instrument (the EU ETS)."

17. The logic of this result is recently adopted in the Market Stability Reserve of EU ETS, becoming active as of January 2019. According to this mechanism EU ETS quotas will enter into a reserve if quota prices tends to go below a floor price, while quotas from the reserve will be released if the quota price tends to rise above a given price cap.

7. SUMMARY AND CONCLUDING REMARKS

This paper considers the compatibility of black, green and white certificate markets intended to reduce the emission of CO_2, increase the share of renewables and increase the share of energy saving, respectively. The markets function well together in the sense that a common equilibrium solution exists, where all targets are satisfied (e.g., share of green electricity and share of energy savings/ efficiency increase.) The equilibrium solution adapts to changing targets (e.g., harsher target on energy savings), but it is impossible to determine whether this will lead to more, less, or unchanged consumption of "black," "green" or "white" electricity.

Applying the model to real world data (i.e., a calibrated model based on parameter values determined from the Norwegian electricity market) helps much in determining the effects, but still ambiguous results appear. For instance, increasing the percentage requirement of green and/or white certificates from a zero level, leads at first to an increase in the total consumption of electricity equivalents, thereafter reaches a maximum and then decreases. Furthermore, increasing the percentage requirement of green electricity leads to an increase in green electricity but a reduction in white electricity, and vice versa when the percentage requirement of white electricity increases.

Introduction of a green and/or a white certificate system also leads to sizable redistributions of consumers' and producers' surpluses. The calibrated model shows that an increase of the percentage requirement of green and/or white electricity from a zero level first yields an increase in the consumers' surplus, before it starts to decrease. The increase in the percentage requirement of green electricity also increases the producers' surplus of green electricity, whereas the producers' surplus of white electricity decreases. Likewise, the increase in the percentage requirement of white electricity increases the producers' surplus of white electricity, whereas the producers' surplus of green electricity decreases. The loser is always the producer of black electricity who experiences a reduction in the producers' surplus following from the introduction of the green and white certificates systems.

Whether these markets may be seen as beneficial depends on the motivations for adopting them. The motivations may be many and range from the regulation of market failures to environmental preservation, job creation and innovation with a consideration of distributional equity and political feasibility (Weitzman, 1974, Goulder and Parry, 1908; Fischer and Preonas, 2010). From an economic point of view it is more relevant to relate the three certificate systems to the existence of proper market failures such as climate change (a negative externality) and to uncertainty (Weitzman, 1974) Hence, the adoption of these systems can be seen as attempts to correct for market failures where the cost of this is levied on the producers of fossil energy and end users of energy. The discussion section of this paper indicates that the additional green and white certificate markets on top of the black certificates market are not particularly well suited for addressing the market failure aspects of electricity generation, nor are they beneficial in terms of combining to a hybrid system to address uncertainty.

In addition to Norway, many countries have introduced or are considering introducing certificate systems within their energy sectors (See footnote 4). These systems are created somewhat differently worldwide, but they have, in common with the Norwegian case, a process where the certificates are tradable and the green and white energy targets are set in terms of percentage levels. These characteristics are essential for how the certificate systems work as they act in concert. Hence, the case of Norway is relevant for knowledge transfer, in particular with respect to how adjustments of the percentage requirements will work with respect to the indeterminacy problems noted.

Furthermore, some of the countries have had second thoughts about how well suited these systems are, e.g., the UK is about to replace the green certificates (ROCs) by a feed-in tariff with contracts for differences. Norway has also recently decided that it will stop allowing new projects to enter the green certificates system (while Sweden wants to continue and even increase the use of this system). For such decisions, the Norwegian experience may also be helpful.

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APPENDIX A: EFFECTS OF PARAMETER CHANGES

We consider effects of changes of *α, β* and *τ* on total generation of electricity equivalents, on black electricity generation, on green electricity generation, on white electricity generation (additional electricity saving) and on electricity actually delivered to end users.

Effects on total generation of electricity equivalents (*x*)

Observe from 1), 2) and 3) that $x_b = ((1-\alpha)/(1+\beta))x$, $x_g = (\alpha/(1+\beta))x$ and $x_w = (\beta/(1+\beta))x$. Substituting these expressions into 6) we have

$$p(x) = \left(1 - \frac{\alpha}{1+\beta} - \frac{\beta}{1+\beta}\right)C_b^{'}\left(\frac{1-\alpha}{1+\beta}x, \tau\right) + \frac{\alpha}{1+\beta}C_g^{'}\left(\frac{\alpha}{1+\beta}x\right) + \frac{\beta}{1+\beta}C_w^{'}\left(\frac{\beta}{1+\beta}x\right)$$

Total differentiations of 6) with respect to *α*, *β* and *τ*, give

$$\frac{dx}{d\alpha} = \frac{\frac{1}{1+\beta}\left\{p_{gc} + \left[\alpha C_g^{"} - (1-\alpha)\varsigma_b^{"}\right]\frac{x}{1+\beta}\right\}}{D}$$

$$\frac{dx}{d\beta} = \frac{\frac{1}{(1+\beta)^2}\left\{p_{wc} - \alpha p_{gc} + \left[\beta C_w^{"} - (1-\alpha)^2 C_b^{"} - \alpha^2 C_g^{"}\right]\frac{x}{1+\beta}\right\}}{D}$$

$$\frac{dx}{d\tau} = \frac{(1-\alpha)C_{b,\tau}^{"}}{(1+\beta)D} < 0$$

where

$$D = p^{'} - \frac{(1-\alpha)^2}{(1+\beta)^2}C_b^{"} - \frac{\alpha^2}{(1+\beta)^2}C_g^{"} - \frac{\beta^2}{(1+\beta)^2}C_w^{"} < 0$$

Inspection of signs shows that both $(dx/d\alpha)$ and $(dx/d\beta)$ are indeterminate when applying the general functional forms assumed in the model. However, $(dx/d\tau)$ is negative, i.e., an increase in the carbon price will definitely lead to a reduction in the total amount of electricity equivalents generated.

Effects on black electricity generation (x_b)

Observe from 1), 2) and 3) that $x = ((1+\beta)/(1-\alpha))x_b$, $x_g = (\alpha/(1-\alpha))x_b$, and $x_w = (\beta/(1-\alpha))x$. Substituting into 6) and taking total differentials with respect to *α*, *β* and *τ*, we obtain

$$\frac{dx_b}{d\alpha} = \frac{\frac{1-\alpha}{(1+\beta)^2}\left\{p_{gc} + \left[\alpha C_g^{"} + \beta^2 C_w^{"} - (1+\beta)^2 p'\right]\frac{x_b}{(1-\alpha)^2}\right\}}{D} < 0$$

$$\frac{dx_b}{d\beta} = \frac{\frac{1-\alpha}{(1+\beta)^2}\left\{\frac{p_{wc} - \alpha p_{gc}}{1+\beta} + \left[\beta C_w^{"} - (1+\beta)p'\right]\frac{x_b}{(1-\alpha)}\right\}}{D}$$

$$\frac{dx_b}{d\tau} = \frac{(1-\alpha)^2 C''_{b,\tau}}{(1+\beta)^2 D} < 0$$

Inspection of signs shows that $(dx_b/d\alpha)$ is negative, i.e., an increase in the percentage requirement for green electricity will definitely lead to less black electricity generation.[18] Furthermore, $(dx_b/d\beta)$ is indeterminate, while $(dx_b/d\tau)$ is negative.

Effects on green electricity generation (x_g)

Observe from 1), 2) and 3) that $x = ((1+\beta)/\alpha)x_g$, $x_b = ((1-\alpha)/\alpha)x_g$, and $x_w = (\beta/\alpha)x_g$. Substituting into 6) and taking total differentials with respect to α, β and τ, we obtain

$$\frac{dx_g}{d\alpha} = \frac{\dfrac{\alpha}{(1+\beta)^2}\left\{p_{gc} + \left[(1+\beta)^2 p' - (1-\alpha)C''_b - \beta^2 C''_w\right]\dfrac{x_g}{\alpha^2}\right\}}{D}$$

$$\frac{dx_g}{d\beta} = \frac{\dfrac{\alpha}{(1+\beta)^2}\left\{\dfrac{p_{wc} - \alpha p_{gc}}{1+\beta} + \left[\beta C''_w - (1+\beta)p'\right]\dfrac{x_g}{\alpha}\right\}}{D}$$

$$\frac{dx_g}{d\tau} = \frac{\alpha(1-\alpha)C''_{b,\tau}}{(1+\beta)^2 D} < 0$$

Inspection of signs shows that $(dx_g/d\alpha)$ and $(dx_g/d\beta)$ are indeterminate, while $(dx_g/d\tau)$ is negative.

Effects on white electricity generation (electricity saving) (x_w)

Observe that $x = ((1+\beta)/\beta)x_w$, $x_b = ((1-\alpha)/\beta)x_w$, $x_g = (\alpha/\beta)x_w$. Substituting into 6) and taking total differentials with respect to α, β and τ obtain

$$\frac{dx_w}{d\alpha} = \frac{\dfrac{\beta}{(1+\beta)^2}\left\{p_{gc} + \left[\alpha C''_g - (1-\alpha)C''_b\right]\dfrac{x_w}{\beta^2}\right\}}{D}$$

$$\frac{dx_w}{d\beta} = \frac{\dfrac{\beta}{(1+\beta)^2}\left\{\dfrac{p_{wc} - \alpha p_{gc}}{(1+\beta)} + \left[(1+\beta)p' - (1-\alpha)^2 C''_e - \alpha^2 C''_w\right]\dfrac{x_w}{\beta^2}\right\}}{D}$$

$$\frac{dx_w}{d\tau} = \frac{\beta(1-\alpha)C''_{b,\tau}}{(1+\beta)^2 D} < 0$$

Inspection of signs shows that $(dx_w/d\alpha)$ and $(dx_w/d\beta)$ are indeterminate, while $(dx_w/d\tau)$ is negative.

18. This result is a generalization of a result reported earlier in Amundsen and Mortensen (2001, 2002).

Effects on electricity generation (x_b+x_g)

Considering the effect on the sum of black and green electricity generation, we find

$$\frac{d(x_b+x_g)}{d\alpha}=\frac{\frac{1}{(1+\beta)^2}\left\{p_{gc}+\left[\alpha C_g^{"}-(1-\alpha)C_b^{"}\right]\frac{x_b}{(1-\alpha)}\right\}}{D}$$

$$\frac{d(x_b+x_g)}{d\beta}=\frac{\frac{1}{(1+\beta)^2}\left\{\frac{p_{wc}-\alpha p_{gc}}{(1+\beta)}+\left[\beta C_w^{"}-(1+\beta)p'\right](x_b+x_g)\right\}}{D}$$

$$\frac{d(x_b+x_g)}{d\tau}=\frac{(1-\alpha)C_{b,\tau}^{"}}{(1+\beta)^2 D}<0$$

Inspection of signs shows that $(d(x_b+x_g)/d\alpha)$ and $(d(x_b+x_g)/d\beta)$ are indeterminate, while $(d(x_b+x_g)/d\tau)$ is negative.

APPENDIX B: A CALIBRATED MODEL

The demand function f is specified as a Cobb-Douglas function:

$$x^D = A^D p^{\varepsilon} = f(p),$$

where A^D is the calibration factor, ε is the elasticity of demand and $p=p_e+(\alpha/(1+\beta))p_{gc}+(\beta/(1+\beta))p_{wc}$. The supply function h for black electricity is assumed given by

$$x_b^S = A^b (p_e)^{\kappa_b} = h(p_e)$$

where A^b is the calibration factor and κ_b is the supply elasticity. The supply function g for green electricity is assumed given by

$$x_g^S = A^g (p_e+p_{gc})^{\kappa_g} - \xi_g = g(p_e+p_{gc})$$

where A^g is the calibration factor, κ_g is the supply elasticity and ξ_g represents the intercept for this kind of electricity. The supply function u for electricity saving is assumed given by

$$x_w^S = A^w (p_e+p_{wc})^{\kappa_w} - \xi_w = u(p_e+p_{wc})$$

where A^w is the calibration factor, κ_w is the supply elasticity and ξ_w is the intercept for this kind of electricity.

Hence, total supply of electricity equivalents is given by

$$x^S = x_b^S + x_g^S + x_w^S$$

and market equilibrium requires $x^D = x^S$, or alternatively expressed $f(p)=h(p_e)+g(p_e+p_{gc})+u(p_e+p_{wc})$.

Furthermore, equilibrium in the wholesale market, the green certificates market and the white certificates market, respectively, requires

$$\frac{(1-\alpha)}{(1+\beta)} f(p) = h(p_e)$$

$$\frac{\alpha}{(1+\beta)} f(p) = g(p_e + p_{gc})$$

$$\frac{\beta}{(1+\beta)} f(p) = u(p_e + p_{wc})$$

The parameters and calibrated values of demand and supply are applied in the analysis. The quantities are in TWh, and the prices are in 0.01 NOK per kWh.

$$\varepsilon = -0.2,\ \kappa_b = 0.3,\ \kappa_g = 0.25,\ \kappa_w = 0.2,\ A^d = \frac{x_0^d}{(p_0)^{\varepsilon}} = \frac{120}{20^{-0.2}} = 219,$$

$$A^b = \frac{x_{b,0}^s}{(p_{e,0})^{\kappa_b}} = \frac{120}{20^{0.3}} = 48.8,\ A^g = \frac{x_{g,10}^s}{(p_{g,10})^{\kappa_g} - (p_{g,0})^{\kappa_g}} = \frac{10}{20^{0.25} - 35^{0.25}} = 31.5,$$

$$A^w = \frac{x_{w,10}^s}{(p_{w,10})^{\kappa_w} - (p_{w,0})^{\kappa_w}} = \frac{10}{20^{0.2} - 35^{0.2}} = 46.4,\ \xi_g = A^g (p_{g,0})^{\kappa_g} = 31.5(20)^{0,25} = 66.6,$$

$$\xi_w = A^w (p_{w,0})^{\kappa_w} = 46.4(20)^{0,2} = 84.4$$

Calibration is based on prices and quantities in the base year (denoted by 0) and in expected values 10 years ahead (denoted by 10). For the case of $\alpha = 0.2, \beta = 0.1$, marginal costs in equilibrium are given by $C_b^{'} = 21.4$, $C_g^{'} = 86.1$ and $C_w^{'} = 68.0$, with corresponding certificate prices given by $p_{gc} = 64.7$ and $p_{wc} = 46.6$.

APPENDIX C: SENSITIVITY ANALYSIS

To check the robustness of the model we investigate the sensitivities of the supply elasticities. In part, the supply elasticities reflect the assumptions on the functional forms of marginal generation costs of green, white and black electricity i.e. a higher supply elasticity increases the curvature and the steepness of the marginal cost functions. Table C. 1. shows the elasticities used in the sensitivity analysis.

It turns out that the results obtained are very robust when changing the supply elasticities used. This can be seen from Table C.2. that shows the percentage deviances of electricity generated compared to the Base Case when $\alpha=\beta=0{,}2$.

The high degree of robustness can also be seen from Figure C.1. and Figure C. 2. These show the development of quantities as α and β are expanded simultaneously ($\alpha=\beta$). Hence, comparing with the Base Case for $\alpha=\beta$ in Figure 3, we see that the profiles of the graphs are the same even though quantities are slightly changed. Furthermore, it also turns out that the same degree of robustness is present for the other cases discussed (partial change of α keeping β and τ constant, partial change of β keeping α and τ constant, and partial change of τ keeping α and β constant). The same goes for changes of the demand elasticity. For the sake of brevity these results are not shown, but they can be obtained from the authors upon request.

Table C. 1: Supply elasticities

Supply elasticity	Base case	High values, Green and White	High value, Black
Green el. (κ_g)	0,25	0,7	0,25
White el. (κ_w)	0,2	0,7	0,2
Black el. (κ_b)	0,3	0,3	0,7

Table C. 2: Percentage quantitative deviances from base case when $\alpha = \beta = 0{,}2$

Quantity of Electricity	Base case elasticity	High values of Green and White elasticities	High value of Black elasticity
Green (x_g^S)	100	99,9	97,7
White (x_w^S)	100	99,9	97,7
Black (x_b^S)	100	102,5	97,7
Total (x^S)	100	101,3	98,1

Figure C. 1: Generation and consumption of black, green and white electricity with simultaneous increase of α and β, high supply elasticities of green and white electricity

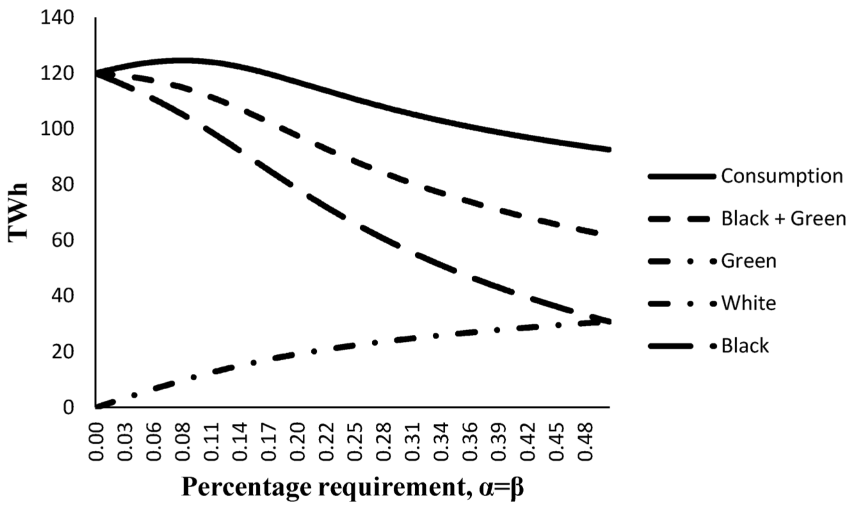

Figure C. 2: Generation and consumption of black, green and white electricity with simultaneous increase of α and β, high supply elasticity of black electricity