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Simultaneous use of black, green, and white certificates systems: A rather messy business

By

Eirik S. Amundsen[1] and Torstein Bye[2]

Abstract[3]

We formulate a model with black, green and white certificates markets that function in conjunction with an electricity market. The markets function well in the sense that a common equilibrium solution exist, where all targets are satisfied (e.g. share of green electricity and share of energy saving/ efficiency increase.) The equilibrium solution adapts to changing targets (e.g. harsher target on energy saving), but it is in general impossible to tell whether this will lead to more, less, or unchanged consumption of ”black”, ”green” or ”white” electricity. These, markets give thus a poor guidance for future investments in green and white electricity. In order to get clear cut results, specific assumptions of parameter values and functional forms are needed. An example of this, based on a calibrated model founded on Norwegian data, is provided in the article. Also, gains and losses in terms of consumer’s and producer’s surpluses are calculated.

JEL classifications: C70; Q28; Q42; Q48

Key words: renewable energy, electricity, Green Certificates, White Certificates

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1. Introduction

Many countries have set targets on greenhouse gas emission, share of renewables and share of energy saving (energy efficiency). For these purposes various market based mechanisms have been proposed and implemented. Apart from the well-established emission permit systems ("black" certificates) designed to curb greenhouse gas emissions, so called "green" and "white" certificates systems have also been put into use[4]. Green certificates systems are designed to take care of the target on renewables, while white certificates are intended for achieving the energy saving's target. Energy saving is to be understood as additionally generated saving as compared with what would otherwise come about due to increasing energy prices[5].

Black, green and white certificates have that in common that the price of the certificate is determined in 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 receive a subsidy in terms of marketable certificates (handed out free of charge) while the purchasers of electricity and energy saving (end-users/ retailers of energy) are paying a tax in terms of obligatory purchases of certificates. Hence, the green and white certificates systems are self-contained in the sense that taxation and subsidization takes place within the energy market itself without involving the government directly in terms of revenues (contrary to the case of the black certificate system).

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[4] The EU "black" certificate system (EU ETS) is the most developed system for carbon emissions and has been around since 2005. Green certificates 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 certificates systems may be found in France ("Certificates d'Economie d'Eenergie"), Italy ("Titoli di Efficienza Energetica") and the UK ("Energy Efficiency Commitment").

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

There exists an abundant literature on the functioning of black certificates systems (see e.g. Ellerman, 2010). Also, a sizable literature on green certificates 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)). Some of the literature deals with the interplay between the green certificates market and the electricity market (e.g. Bye (2003), Nese (2003), Amundsen, Baldursson and Mortensen (2006), Fischer (2009), Fischer and Preonas, (2010)), while some take account of both the electricity market, the black certificates market and the green certificates market (e.g. Amundsen and Mortensen (2001, 2002), Unger and Ahlgren (2005), Böhringer and Rosendahl (2010)). Recently, some literature has emerged dealing with all certificates systems taken together (Meran and Wittmann (2012)).

Considering each by itself, all certificate systems may under given conditions achieve the targets[6] they are designed for, but as the targets for the shares of renewables and energy savings typically are set in percentages, one cannot immediately conclude anything about the quantities of renewables or energy saving resulting from, say, harsher targets. For instance, it has been shown that an increase of 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 and harsher targets of renewables may even lead to increasing electricity consumption (Bye, 2003, Fischer, 2009).

Apart from 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 certificates system, while Böhringer and Rosendahl (2010)) show that a green certificate system on top of a black certificate system serves the dirtiest power technologies as compared with a black certificate system only. 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

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[6] For a discussion of multiple targets and overlapping policies, see Fischer and Preonas (2010).

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 the green certificates systems further complicate 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 set out to investigate 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 are actually adopted or planned used in several countries. Hence, it should be of interest to investigate whether these systems at least are 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), Meran and Wittmann (2012), we set out 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 saving being generated, or whether a harsher target of energy saving leads to more or less green electricity being generated. Likewise, we investigate what effects harsher target on black electricity reduction has on green and white electricity generation.

In order to answer questions like these, we formulate a stylized analytical model and consider equilibrium solutions where the various targets are complied with for any chosen level of the targets. It turns out, however, that not very much can be said at all analytically when considering the market effects on the various kinds of electricity products: “green electricity”, “black electricity” and “white electricity” (electricity saving) following these supporting systems. Since analytical results are ambiguous we, therefore, go on to investigate the systems in a numerical model taking account of realistic data and parameter values compiled from the Norwegian electricity sector. More cut results now appear even though some ambiguities remain. Along with this we also study distributional effects in terms of consumer’s surplus, producer’s 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 certificates (TGC) market and a tradable white certificates (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 get one TGC per unit of green electricity delivered. This may be sold on the TGC market. Producers of black electricity only get the wholesale price.

Electricity producers also provide energy saving (“white electricity”) through e.g. ancillary services and installation of smart devices and get a price per unit electricity saved valued at the wholesale price. In addition, they get 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 saving 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 kinds 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 purchase 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 emission stemming from the generation of black electricity is regulated by a tax or a permit system. To take account of this the price (tax or permit price) of carbon emission 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 saving (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“)

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[7] 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 $(\partial^2 C_b / \partial x_b \partial \tau) = C_{x_e \tau}^{''} > 0$[8]

$C_g(x_g) =$ Industry cost function for green electricity, where $(\partial C_g / \partial x_g) = C_g^{'} > 0$, $(\partial^2 C_g / \partial x_g^2) = C_g^{''} > 0$

$C_w(x_w) =$ Industry cost function for white electricity, where $(\partial C_w / \partial x_w) = C_e^{'} > 0$, $(\partial^2 C_w / \partial x_w^2) = C_w^{''} > 0$[9]

In aggregate, producers maximize profit:

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

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

$$p_e = C_b^{'},\ p_e + p_{gc} = C_g^{'},\ p_e + p_{wc} = C_w^{'}$$

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

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[7] 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.

[8] 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.

[9] 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 wind mills. White electricity is presumably also getting more and more costly at the margin as electricity saving is 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.

For each unit of electricity equivalents delivered to end users, retailers have to 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 and the 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 TWC are 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

1) $x = x_b + x_g + x_w$

2) $x_g = \alpha(x_b + x_g)$

3) $x_w = \beta(x_b + x_g)$

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

5) $p_e = C_g^{'}$; $p_e + p_{gc} = C_g^{'}$; $p_e + p_{wc} = C_w^{'}$

Observe that the TGC and the 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:

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

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 and discussion

In Appendix A we present the total differentials with respect to the certificate shares α, β and τ. These show that the effects in general depend on all the supply elasticities, the demand elasticity and the parameters α, β and τ. Further, the model shows 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 saving (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 fact, as shown in Appendix A, not very much can be said at all of such effects. Table 1 summarizes the results of the analysis.

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

In particular, Table 1 shows that an increase of the percentage requirement for green electricity, α, does not necessarily lead to increased generation of green electricity, nor does an increased percentage requirement for white electricity, β necessarily lead to more electricity saving. Hence, if the increase of the percentage requirement of green electricity leads to a reduced demand for electricity, the generation of green electricity may fall 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 drop if electricity demand decreases. The only general clear cut result on quantity effects from introducing a TGC and a TWC system is that the generation of black electricity definitely will fall when increasing the percentage requirement for green electricity.

Apart from this, the analysis shows that an increase of 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 saving, which may be seen as unwanted side effects of the carbon price increase. These results are due to the design of the TGC and the TWC systems. In particular, from 6) we have 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 kinds of electricity in the correct proportions. As the carbon price increases it merely shifts the weighted marginal cost curve upwards and gives rise to a higher end user price of electricity. This leads to less consumption of electricity equivalents and a unilaterally reduction of all kinds of electricity as these are set in fixed proportions.

Table 2 Effects of increasing values of α , β , and τ : Special cases

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

Other compatibility effects may be seen from Table 2 that summarizes various special cases. For instance, one may observe that an increase of the percentage requirement for electricity saving, 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 equivalents all taken together 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 result of this analysis is that the total demand for electricity equivalents actually may 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 saving. It turns out that this is not only a theoretical problem but may well be the case of a real world setting. Indeed, this has been shown in Bye (2003) using a numerical model of a TGC market calibrated on data for the Norwegian electricity market. In order to investigate this important aspect further for the case of both a TGC market and a TWC market we expand the model in Bye (2003) in the following section. This numerical model may then serve as an example of how electricity generation and social surplus may be affected by introducing simultaneous functioning black-, green-, and white certificates in an economy.

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

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

Also, 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). As shown in the simpler version of the numerical model (Bye, 2003), the derived empirical results are quite robust against a wide variation of elasticities. Since we, in the present paper, are focusing on general results, we only report the results using the most relevant Norwegian market data.

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. $\beta = 0.2$. Secondly, 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. $\alpha = 0.2$. Thirdly, we investigate the effects on the various electricity components of increasing the percentage requirement for both green and white electricity simultaneously. Fourthly, we investigate the effects of increasing the CO2-tax and fifthly we investigate the effects of increasing the CO2-tax when there are no markets for green and white certificates.

As can be 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. Furthermore, the consumption of total electricity equivalents will first increase, thereafter reach a maximum and then fall off. 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 falls.

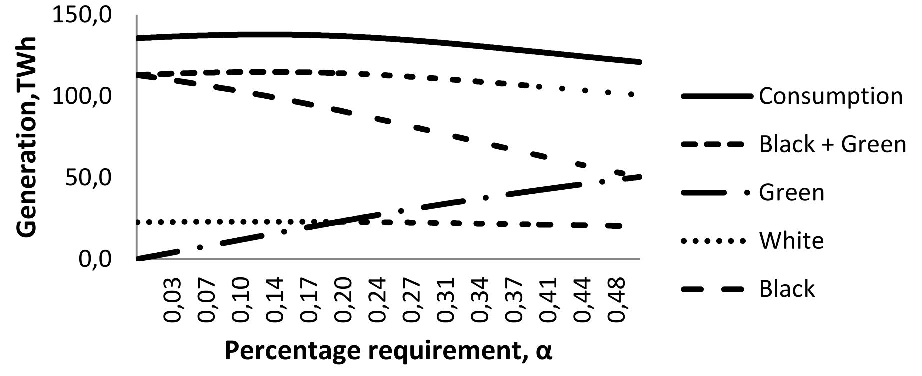


Fig. 1. Generation and consumption of black, green and white electricity with increasing α while keeping β=0.2

Likewise, as seen from Figure 2, an increase of the percentage requirement for white certificates while keeping α=0,2 will lead to reductions of the generation of both green and black electricity, while the generation of white electricity will increase. Also, for this case the consumption of total electricity equivalents (including white electricity) will first increase, thereafter reach a maximum and then fall off as the percentage requirement for white certificates increases.

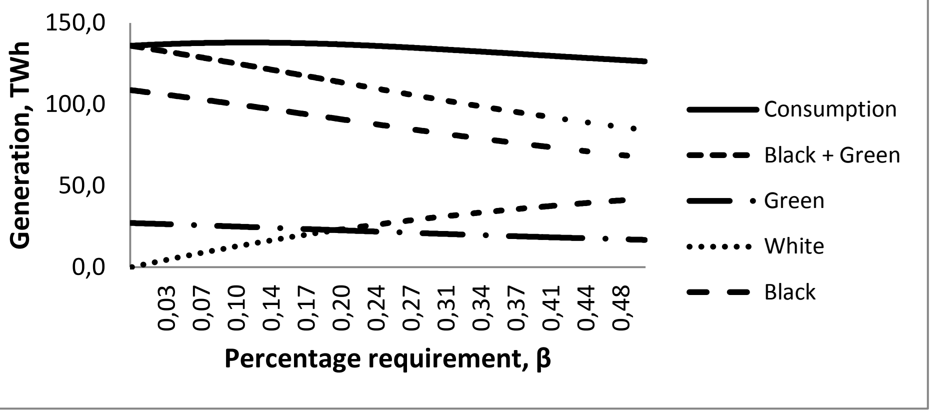


Fig. 2. Generation and consumption of black, green and white electricity with increasing β, while keeping α=0.2

Figure 3, shows that a simultaneous expansion of the percentage requirements for both green and white certificates results in increases of 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 fall off.

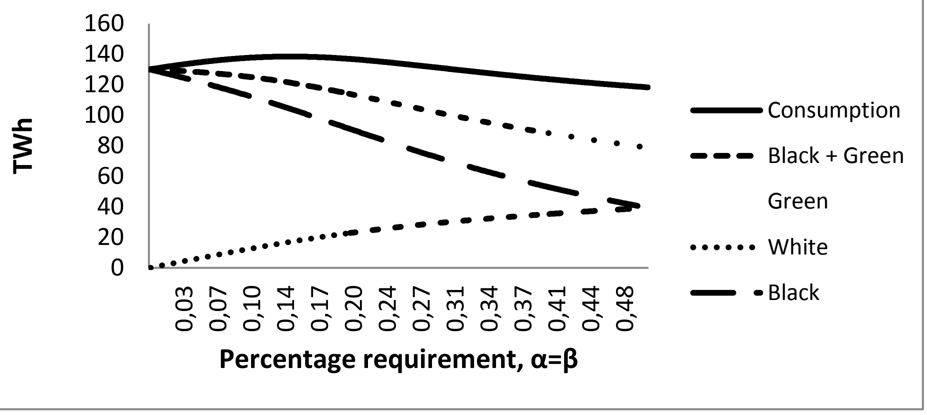
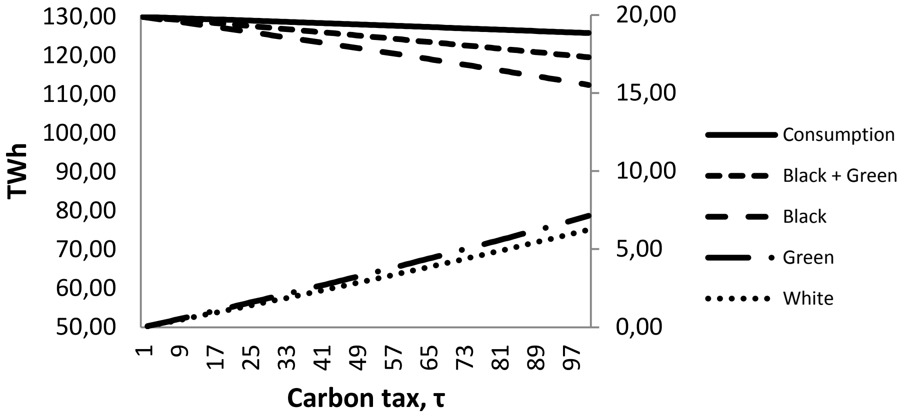


Fig. 3. Generation and consumption of black, green and white electricity with simultaneous increase of α and β

As already noted and shown analytically in Appendix A, an increase of the CO_2-tax leads to a unilateral reduction of all kinds of electricity generation and of the total consumption of electricity equivalents. In particular, this means that both green and white electricity generation actually are 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 of the CO_2-tax would lead to a reduction of the generation of black electricity, but also an *increase* of green and white electricity. Thus, the unwanted effects from the above case are avoided, as is illustrated in Figure 4. 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.

Fig. 4. Generation and consumption of black, green and white electricity with increasing carbon tax, τ, and no certifictes markets



The results of this section this far are summed up in Table 3.

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

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

(i), (ii), (iii) Total consumption of electricity equivalents, x, first increases, reaches a maximum at α=0,128, β=0.113 and $\alpha = \beta$=0.141, respectively and then falls off. The same is true for the sum of green and black electricity for increasing values of α. The sum reaches a maximum for $\alpha = 0{,}129$.

For all cases of increases of α and β considered, the end user price of electricity equivalents at first fall, thereafter reaches a minimum and then increases. Corresponding to this there are changes of the various kinds of surpluses; i.e. consumer's surplus, producer's surplus, tax revenue and total social surplus (the sum of surpluses). For all cases considered the social surplus drops. However, it should be noted that the benefit of greenhouse gas reductions stemming from the various policies has not been included, so one cannot draw the immediate conclusion that the adopted policies are welfare worsening[10].

Apart from this it may be interesting to note that the consumer's surplus actually increases for increasing values of α and β, before it starts to fall again. The looser in this setting is the producers of black electricity, in particular. Hence, producer's surplus for the producers of black electricity is mostly transferred to consumer's surplus. Also, 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 producer's surplus for green electricity is decreasing (see Fig. 5). 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.

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[10] For Norway, however, we are very close to be 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 rest 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.

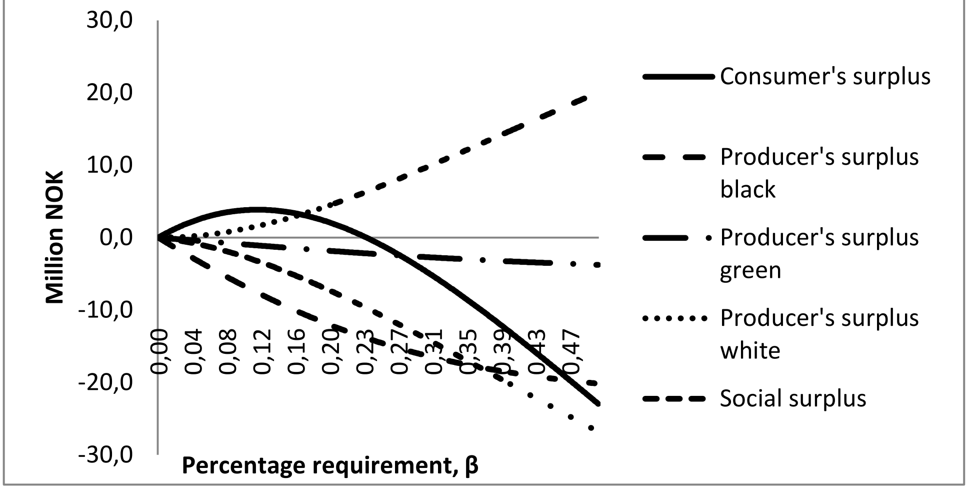

Fig. 5. Change in welfare components due to harsher targets of energy saving/ efficiency

6. Summary and concluding remarks

This paper considers the compatibility of black, green and white certificates systems intended to reduce the emission of CO_2, increase the share of renewables and stimulate energy saving, respectively. The most important general conclusion that can be drawn from this analysis is probably that not very much can be said at all about how these instruments work together. Hence, it is impossible to tell whether introduction of such markets on top of an electricity market will lead to more, less or unchanged consumption of electricity in general and green and white electricity in particular. These markets, thus, give a poor guidance for future investments in green and white electricity, which in itself should worry policy makers. However, a robust specific conclusion is that the generation of "black electricity" will definitely fall as the percentage requirement of green electricity increases (whereas this is not the case if the percentage requirement of white electricity increases). Another robust conclusion is that an increase of the certificate price (carbon price) of black electricity leads to a reduction of both black, green and 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 a great deal, but still ambiguous results appear. For instance, increasing the percentage requirement of green and/or white certificates from zero level, leads at first to an increase of the total consumption of electricity equivalents, thereafter reaches a maximum and then falls off. Furthermore, increasing the percentage requirement of green electricity leads to an increase of green electricity but a reduction of 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 consumer’s and producer’s surpluses. The calibrated model shows that an increase of the percentage requirement of green and / or white electricity from zero level first gives rise to an increase of consumer’s surplus, before it starts to fall off. The increase of the percentage requirement of green electricity also increases the producer’s surplus of green electricity, whereas the producer’s surplus of white electricity falls. Likewise, the increase of the percentage requirement of white electricity increases the producer’s surplus of white electricity, whereas the producer’s surplus of green electricity falls. The looser is always the producers of black electricity that experience reductions of the producer’s surplus following from the introduction of the green and white certificates systems.

Following from this analysis one may wonder whether it would be economically beneficial to introduce green and white certificates on top of a system of black certificates (i.e. carbon prices). One view would be that these systems should at least have predictable effects on energy generation in theory as a guidance for the industry’s investment. This paper shows that they do not. Related to this discussion is the question of why it is optimal to have several targets for energy use, when the essential target is to reduce the emission of greenhouse gases (see Fischer and Preonas, 2010). Additional specific targets on share of renewables and energy saving/ efficiency improvements may function as un-necessary and costly constraints. A simple observation is that a carbon tax or a black certificates market itself may generate the preferred effects, i.e. an increase of the carbon price will reduce the generation of black electricity, but at the same time also increase the share of green electricity, as well as increasing the level of energy saving through price increases. Hence, as pointed out by Tinbergen (1952) and discussed by Fischer and Preonas (2010), a single instrument (e.g. a Pigouvian tax) is preferable from the point of view of society[11] if there is only one target, such as the target of reducing the emission of greenhouse gases.

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

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

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

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

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

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

where

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

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[11] However, confronted with uncertainty it may well be optimal to combine instruments, such as a quotas-system and a price-system (maximum and minimum quota prices). See e.g. Roberts and Spence (1974).

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 of the carbon price will definitely lead to a reduction of 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 $x_w = (\beta/(1-\alpha))x_b$. Substituting into 6) and taking total differentials with respect to α , β and τ we arrive at

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

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

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

Inspection of signs shows that $(dx_b/d\alpha)$ is negative, i.e. an increase of the percentage requirement for green electricity will definitely lead to less black electricity generation.[12] 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 arrive at

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

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

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

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

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 we arrive at

$$\frac{dx_w}{d\alpha} = \frac{\frac{\beta}{(1+\beta)^2}\left\{p_{gc} + \left[\alpha C_g^{\overset{'}{''}} - (1-\alpha)\mbox{Ç}_b''\right]\frac{x_w}{\beta^2}\right\}}{D}$$

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

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

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

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

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

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

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

Parameters and calibrated values of demand and supply applied in the analysis (quantities are in TWh and prices in øre (0,01 NOK)).

$$\varepsilon = -0{,}2\,,\ \kappa_b = 0{,}3\,,\ \kappa_g = 0{,}25\ \kappa_w = 0{,}2\,,\ A^d = \frac{x_0^d}{(p_0)^{\varepsilon}} = \frac{120}{20^{-0{,}2}} = 219 \qquad ,$$

$$A^b = \frac{x_{b,0}^s}{(p_{e,0})^{\kappa_b}} = \frac{120}{20^{0{,}3}} = 48{,}8\,,\ A^g = \frac{x_{g,10}^s}{(p_{g,10})^{\kappa_g} - (p_{g,0})^{\kappa_g}} = \frac{10}{20^{0{,}25} + 35^{0{,}25}} = 31{,}5\,,$$

$$A^w = \frac{x_{w,10}^s}{(p_{w,10})^{\kappa_w} - (p_{w,0})^{\kappa_w}} = \frac{10}{20^{0{,}2} + 35^{0{,}2}} = 46{,}4\,,$$

$$\xi_g = A^g (p_{g,0})^{\kappa_g} = 31{,}5(20)^{0{,}25} = 66{,}6\,,\ \xi_w = A^w (p_{w,0})^{\kappa_w} = 46{,}4(20)^{0{,}2} = 84{,}4$$

Quantities are in TWh and prices in øre (i.e. 0,01NOK). Calibration is based on prices and quantities in base year (denoted by 0) and in expected values 10 years ahead (denoted by 10).

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