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Green Serves the Dirtiest
On the Interaction between Black and Green Quotas

Abstract:
Tradable black (CO_2) and green (renewables) quotas gain in popularity and stringency within climate policies of many OECD countries. The overlapping regulation through both instruments, however, may have important adverse economic implications. Based on stylized theoretical analysis and substantiated with numerical model simulations for the German electricity market, we show that a green quota imposed on top of a black quota does not only induce substantial excess cost but serves the dirtiest power technologies as compared to a black quota regime only.

Keywords: Emissions Trading; Tradable Green Certificates; Overlapping Regulation

JEL classification: D61; H21; H22; Q58

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1. Introduction

Combining environmental effectiveness and economic efficiency, tradable quota systems have become a central pillar in environmental policies of OECD countries.

As a prime example, the European Union (EU) started off a large-scale international CO_2 emission trading scheme in 2005 for compliance with the Kyoto Protocol. The stringency of the EU trading scheme will be further increased in order to achieve the outspoken EU policy goal of a greenhouse gas emission cutback by 20 per cent in 2020 (compared to 1990).[1] Likewise, proposals for domestic emission cap-and-trade systems are expected to come into force in the US under the new Obama administration following up on regional programs that have been already adopted by Northeastern (RGGI 2008) and Western states (WCI 2008).

Along with emissions trading systems, various OECD countries pursue a substantial increase in their shares of renewable energy sources as an important complementary measure in the "fight against climate change" (European Commission 2008) and for other – more vague – reasons such as energy security or strategic technological innovation. Within its ambitious "20-20-20" plan, the EU promises to increase the share of renewables in overall EU energy consumption to 20 per cent by 2020.[2] The EU proposal specifies national renewable targets for each member state, which can be met by over-fulfilment in other countries through transfer of guarantees of origin (GO). The GO system can be combined with existing renewable support mechanisms such as feed-in tariffs or tradable green certificates (TGC), also referred to as renewable portfolio standard (RPS) (Neuhoff et al., 2008).[3] The US also aims to increase its share of renewable energy, and according to Fischer (2006) nearly half of the US states have established an RPS or a state-mandated target for renewables.

As the simultaneous use of tradable *black* (CO_2) and *green* (renewables) quotas gain in popularity and stringency, it is important to properly understand not only the economic implications of each specific instrument but also how these instruments interact with respect to policy-relevant variables including technology mixes, carbon values, electricity prices, and overall cost of regulation. Ultimately, the interaction of black and green quotas must be discussed in the context of the prevailing policy targets.

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[1] See http://ec.europa.eu/environment/climat/climate_action.htm.

[2] The "20-20-20" EU strategy postulates a reduction of greenhouse gas emission of 20 per cent, a share of renewable energy sources of 20 per cent, and an increase of energy efficiency of 20 per cent by 2020.

[3] Feed-in tariffs are used in e.g. Germany, France and Spain, whereas TGCs are implemented in e.g. the UK and Italy (Italy also has a feed-in tariff for small plants).

If the main objective of both instruments is to reduce emissions of CO_2, the issue of counterproductive overlapping regulation arises (Tinbergen 1952). In this case, a black quota "stand-alone" is first-best provided there are no other initial distortions and the additional instrument – here a green quota – will be at best redundant but likely generate excess cost.[4] More generally, the latter could be seen as a price tag on green quotas for the composite of objectives different from emission reduction.[5]

In this paper, we investigate the economic impacts of overlapping black and green quotas for the electricity system, which is the key sector targeted by CO_2 emission regulation and promotion of renewable energy. Based on a stylized theoretical model we first derive analytical results for the impacts induced by a green quota which is imposed on a power market already regulated by a black quota. A central result is that renewable quotas improve the performance of the most carbon-intensive power generation technologies as compared to a black quota regulation alone. In other words: Green serves the dirtiest – an implication that protagonists of green quota systems might not like as it could undermine public support for green policies.

Why does supply of the dirtiest technologies increase when the green quota is imposed? The explanation is that policies to increase the share of green power as a first-order effect reduce the profitability of black power producers, and thus decrease their output. However, because total emissions are fixed by the black quota, the price of emissions falls, and this benefits the most emission-intensive technologies the most. As some black producers must increase their output given constant total emissions, the final result is higher output from the dirtiest technologies. We substantiate our theoretical findings with a numerical analysis for the German electricity system where we also quantify the implications of overlapping regulation on excess cost, carbon values and electricity prices.

Our analysis complements several studies that have discussed the effects of combining black and green quotas (see González (2007) for a survey). Amundsen and Mortensen (2001) show within an analytical framework that an increased share of renewables in a closed electricity market will lead to lower CO_2 prices. NERA (2005) provides a thorough discussion about how green quota schemes may

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[4] Böhringer et al. (2008) elaborate on the excess cost of overlapping regulation within the EU arising from the imposition of emission taxes on top of emission quota systems to reach the EU climate policy targets. Böhringer and Lange (2005) examine the trade-off between efficiency and harmonization of allocation rules across EU member states.

[5] Note that these other objectives – if properly defined – are nevertheless likely to be met in a more cost-effective way. For example, promotion of R&D research in green technologies would call for specific R&D subsidies rather than broad-based subsidies to green production. As Sorrell and Sijm (2003) point out, it is important that the objectives and trade-offs within the policy mix are explicit. See Hahn (1986) for a discussion of designing markets in the case with multiple objectives, and Bennear and Stavins (2007) for a discussion of using multiple instruments in a second-best world.

affect the electricity market when the black quota is already in place (see also Morthorst (2001) for an early contribution). A few simulation studies have quantified the effects of combining emission trading and support schemes for green technologies, including Rathmann (2007) and Abrell and Weigt (2008). However, none of these studies have laid out how a green quota serves the dirtiest power producers.

2. Theoretical analysis of overlapping regulation

In our theoretical analysis we consider a partial equilibrium model of a closed, competitive power market, with *m* producers of 'green' power and *n* producers of 'black' (non-green) power. Let *G* and *B* denote the set of green and black power producers, respectively. Power producers have cost functions $c^i(q^i)$, where q^i denotes production in firm *i*. As usual, cost functions are assumed to be twice differentiable and convex with $c^i_q > 0$ and $c^i_{qq} > 0$. Let q, q^G and q^B denote total production (and consumption), total green production and total black production, respectively.

We further assume that emissions e^i in each firm are proportional to production, i.e., $e^i = a^i \cdot q^i$, where a^i denotes the emission intensity of firm *i*.[6] There are no emissions from green power production, i.e., $a^i = 0$ for $i \in G$ ($a^i \geq 0$ for $i \in B$). Let $p^E = D(q)$ ($D' < 0$) denote the inverse demand function, where p^E is the end-user price of electricity.

Assume now that the government has introduced a ceiling $\hat{e}$ on total emissions from the power sector, implemented through an emission trading system (ETS) where σ denotes the emissions price. Furthermore, assume that a green quota is imposed, so that green power must constitute at least the share α of total power production. Finally, assume that both the ceiling on emissions and the green quota are binding whenever they are imposed.

Let us examine the effects in the power market of imposing the green quota when the ETS is already implemented. The green quota could be thereby implemented in different ways, e.g., via tradable green certificates, uniform or differentiated feed-in tariffs (possibly combined with an end-user tax).

The maximization problem of black and green producers can then be characterized in the following way:

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[6] This assumption is quite realistic in the power market, where each power plant has a fairly fixed conversion rate between energy input and electricity output (except in start-up periods). Moreover, it provides a straightforward interpretation of the term 'dirtiest technology'. Below we will briefly discuss the implications of having a more general cost function $c^i(e^i, q^i)$.

(1) $$Max\left[p^B q^i - c^i(q^i) - \sigma a^i q^i\right] \quad (i \in B)$$

(2) $$Max\left[p^G q^i - c^i(q^i) + \pi^i q^i\right] \quad (i \in G)$$

where p^B and p^G denote the price black and green producers receive respectively, net of direct or indirect taxes/subsidies that do not distinguish between different green or different black technologies.[7] π^i denote technology-specific (direct or indirect) subsidies to green producers. Note that $p^E = p^B + \tau + \tau^B = p^G + \tau + \tau^G$, where τ is a tax (or negative subsidy) on all energy use or production, and τ^B and τ^G are direct/indirect taxes/subsidies on respectively black and green energy production. First-order conditions are then:

(3) $$c^i_{q^i}(q^i) = p^B - a^i\sigma \quad (i \in B)$$

(4) $$c^i_{q^i}(q^i) = p^G + \pi^i \quad (i \in G).$$

Next, we totally differentiate equations (3) and (4) to get:

(5) $$c^i_{q^i q^i}(q^i)dq^i = dp^B - a^i d\sigma \quad (i \in B)$$

(6) $$c^i_{q^i q^i}(q^i)dq^i = dp^G + d\pi^i \quad (i \in G).$$

We examine the case where the green quota α is increased marginally. Because of the binding emission constraint we must have $\sum a^i \cdot dq^i = 0$. Thus, if one black producer reduces production, then there exists some other black producer that increases production. We assume that $dp^B \leq dp^E$, which holds in the absence of new subsidies (or reduced taxes) to end-users or black producers. By multiplying equation (5) by dq^i and then summing up over all $i \in B$ we obtain:

(7) $$\sum_{i \in B}\left(c^i_{q^i q^i}(q^i)\left(dq^i\right)^2\right) = dp^B \sum_{i \in B} dq^i + \sum_{i \in B} a^i dq^i = dp^B dq^B.$$

Assume that $a^i \neq a^j$ for at least one pair (i,j), which implies that $dq^i \neq 0$ for at least one i.[8] The left-hand side of equation (7) is then strictly positive, which means that dq^B and dp^B must have the same sign (and differ from zero). If dq^B is positive, then dq is also positive, and so dp^E must be negative due to the demand function. However, then dp^B is also negative, violating the equation. Consequently, we must have $dq^B < 0$ and $dp^B < 0$.

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[7] By indirect taxes/subsidies, we mainly think of green certificate markets, which provide an extra revenue to green producers and an extra cost to black producers (or to consumers).

[8] If $dq^i = 0$ for all $i \in B$, equation (5) tells us that we must either have $a^i = a^j$ for all i, j, or $d\sigma = 0$. However, $d\sigma = 0$ implies that $0 = dp^B \leq dp^E$, which (from the demand side) is impossible because we have $dq > 0$ whenever $dq^B = 0$. Thus, $dq^i = 0$ for all $i \in B$ implies $a^i = a^j$ for all i, j, in which case there is no meaning in the term 'dirtiest' black technology.

Equation (5) then implies that $d\sigma < 0$, because otherwise we would have $dq^i < 0$ for all $i \in B$. Furthermore, let $\hat{a}$ be defined so that $dp^B - \hat{a}d\sigma = 0$. Then we have from equation (5) that $dq^i < 0$ for all black firms with $a^i < \hat{a}$ and $dq^i > 0$ for all firms with $a^i > \hat{a}$. In other words, the dirtiest technologies increase their production, whereas the least dirty black technologies decrease their output.
We state this main finding in the following proposition:[9]

Proposition

Consider a competitive power market that is initially regulated by a binding emission trading system. Assume that firm-specific emissions are proportional to production. Introducing a binding green quota will then i) decrease total black production, ii) decrease output from the least emission-intensive black technologies, and iii) increase output from the most emission-intensive technologies.

Why do output from the most emission-intensive power producers increase when the green quota is imposed? The basic intuition is that policies to increase the share of green power will, as a first-order effect, reduce the profitability of black power, and thus reduce output from all black producers. However, because of the binding emission ceiling, the second-order effect is a reduction in the price of emissions. This benefits the most emission-intensive technologies the most. Thus, whereas the first-order effect affects all black technologies symmetrically (and negatively), the second-order effect is asymmetrical. As some black producers must increase their output in order to keep total emissions constant, we end up with higher output from the dirtiest technologies. This result is in sharp contrast to the case where there is no ETS in place, in which case all black producers reduce their output (see e.g. Fischer, 2006).

The results above are independent of the policy instrument choice for promoting green power production. The effects on the end-user price of electricity and output from individual green producers, however, depend on the chosen policy. The two most common instruments to stimulate green power production are tradable green certificate (TGC) markets and feed-in tariffs. In Appendix 1 we show that TGC markets and uniform feed-in tariffs financed by an end-user tax on electricity consumption are in fact equivalent. We also show that such policies will increase output from all green power producers.

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[9] With a more complex cost function of the form $c^i(e^i,q^i)$, and standard assumptions about derivatives, the only change would be to replace a^i with $(-c_{qe}/c_{ee})$ in equation (5). Thus, producers with $(-c_{qe}/c_{ee}) > \hat{a}$ would increase their output. The fraction $(-c_{qe}/c_{ee})$ is reduced to a^i in the case with emissions proportional to output.

The effect on the end-user price of electricity is ambiguous (cf. Appendix 1).[10] This is in line with what Fischer (2006) finds when she examines the effects of TGC alone: The sign of the price effect is ambiguous and depends on the supply elasticities of green and black electricity producers. However, the likelihood of a price decrease is higher in our case when an ETS is already in place, because the reduced emissions price has a stimulating effect on black production. Still, a price increase can occur if the black producers have very different emission intensities, and the green producers have much steeper marginal cost than the least emission-intensive black producers.

Most countries with feed-in tariffs differentiate the tariff between technologies. The least mature technologies, such as photovoltaic, typically have a higher tariff than the more mature technologies, such as onshore wind power. In this case, there is no equivalence between TGC and feed-in tariffs, and some green producers may become worse off if their tariff is relatively small and the price of electricity falls.

Finally, as mentioned in the introduction, introducing a green quota in addition to the black quota increases the cost of reducing CO_2 emissions; differentiated feed-in tariffs are thereby more costly than uniform tariffs if the ultimate goal is to reach a certain share of green power (and keep emissions below a certain target). These results are straightforward by economic intuition and easy to show in analytical terms. From a policy perspective, however, the key question remains how large this excess cost turns out as it provides the price tag for other potential benefits of greener power production (e.g., enhanced energy security and technological progress). In the numerical analysis below we quantify the magnitude of the excess cost of overlapping regulation, and leave it up to policy makers to evaluate this cost against potential benefits.

3. Numerical framework

In order to quantify the implications of overlapping green and black quotas and thereby assess the policy relevance of our arguments, we complement our theoretical analysis with numerical simulations based on a partial equilibrium model of the German electricity market. Domestic electricity production is based on a set of discrete power generation technologies covering non-renewable thermal power plants (hard coal, lignite, gas, oil, nuclear) as well as power plants that operate on renewable energies (hydro, wind, solar, biomass, biogas). There is a distinction between extant technologies operating on existing capacities and new vintage technologies that require new investment. Each technology is

[10] If feed-in tariffs are financed by the government, and not by end-users, electricity prices will unambiguously decline.

associated to base, middle, or peak load. Extant technologies of the same load-type trade off with a constant elasticity of substitution (CES), subject to a high substitution elasticity, whereas new vintage production can enter the respective load as a perfect substitute. The different load supplies are then combined towards a CES aggregate of domestic electricity supply, subject to a low substitution elasticity. After accounting for taxes and grid fees the domestic electricity supply together with net imports must satisfy domestic electricity demand.

The model is calibrated to base year data for 2004, as a reference year before the German electricity sector became subject to CO_2 emission reduction requirements under the EU emissions trading scheme. Market data on installed capacities, power supply by technology, electricity imports and exports, final demand as well as electricity prices is taken from the most recent official version of the German energy data collection provided by the Federal Ministry for Economic Affairs and Technology (BMWI, 2008). Technical and economic information on the different power plants is based on the IER technology database (IER, 2008), which includes detailed technology-specific data on installation cost, operating and maintenance cost, thermal efficiencies, and emission coefficients. Future potential capacities for renewable energies stem from the EU GreenX project (GreenX, 2008). Information on load patterns and utilization for the German power sector in the reference year is given by VDEW (2004); German taxes and fees within the electricity sector are reported by BDEW (2008); grid fees are based on the 4th Benchmarking Report of the European Commission (European Commission, 2005).

Cast as a planning problem, the electricity market model corresponds to a nonlinear program that maximizes the sum of producer and consumer surplus. The nonlinear optimization problem can be interpreted as a market equilibrium problem where prices and quantities are defined using duality theory. In this case, a system of (weak) inequalities and complementary slackness conditions replace the minimization operator, yielding a so-called mixed complementarity problem (MCP), see e.g. Rutherford (1995).[11] Two classes of conditions characterize the (competitive) equilibrium for our MCP model: zero profit conditions and market clearance conditions. The former class determines activity levels (quantities) and the latter determines prices. The economic equilibrium features complementarity between equilibrium variables and equilibrium conditions: activities will be operated as long as they break even, positive market prices imply market clearance – otherwise commodities are in excess supply and the respective prices fall to zero.

[11] A major advantage of the mixed complementarity formulation is that it allows for the incorporation of second-best phenomena by relaxing so-called integrability conditions (see Pressman (1970) or Takayma and Judge (1971)) which are inherent to economic models formulated as optimization problem.

Appendix 2 presents a detailed algebraic model formulation. Numerically, the model is implemented in GAMS (Brooke et al., 1987) using PATH (Dirkse and Ferris, 1995) as a solver. The GAMS file and the EXCEL reporting sheet to replicate our results are readily available from the authors upon request.

4. Policy Scenarios and Numerical Results

The motivation for our central case scenarios is provided by the EU's comprehensive "climate action and renewable energy package" to fight climate change (European Commission 2008). Within this package the EU has committed itself to reducing its overall emissions to at least 20 per cent below 1990 levels by 2020. It has also adopted the target of increasing the share of renewables in total energy use to 20 per cent by 2020. The climate action and renewable energy package sets out the contribution expected from each Member State to meeting these targets. Germany as the major CO_2 emitter within the EU is obligated under the Kyoto Protocol and the EU-internal burden sharing agreement to cut back greenhouse gas emissions during 2008-2012 by on average 21 per cent from 1990 levels. Beyond the 1st commitment period, Germany will pursue more stringent emission cutbacks until 2020 (in fact up to 40 per cent from 1990 emission levels) and increase the share of renewable energies in power production up to 30 per cent.

Against this policy background we illustrate the implications of simultaneous black and green quotas for the German electricity market taking a 25 per cent emission reduction vis-à-vis the reference emission level as a starting point (scenario BLACK). We then impose a sequential increase in the renewable energy share of up to 10 percentage points on top of the renewable share emerging from BLACK only (scenario BLACK&GREEN), cf. Table 1.

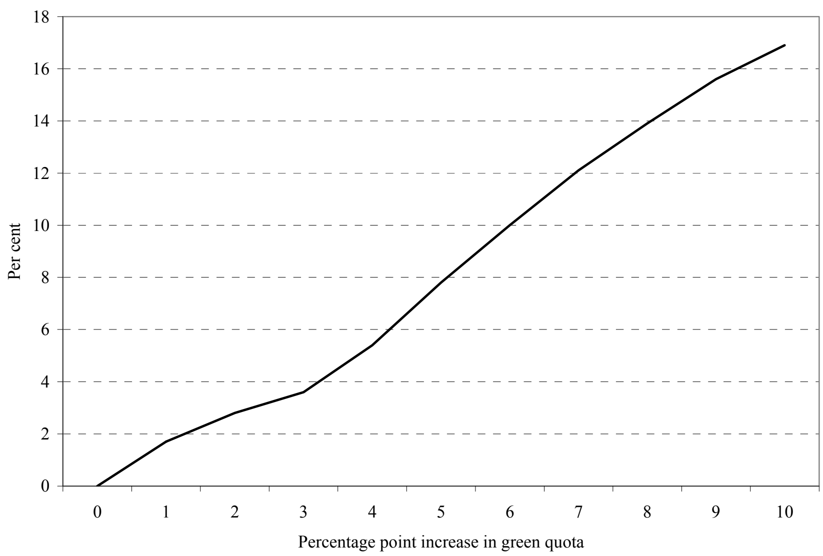
Table 1: Overview of central case scenarios

Scenarios	**Black quota**	**Green quota**
BASELINE	Not assigned	Not assigned
BLACK	25 per cent below BASELINE emission level	Not assigned
BLACK&GREEN	25 per cent below BASELINE emission level	n percentage points increase compared to BLACK, $n \in \{1,10\}$

With the emission constraint in place under scenario BLACK, the share of green power production increases from 11 to 13 per cent. Thus, in scenario BLACK&GREEN the share of green power production increases from 13 to 23 per cent, keeping the emission constraint fixed (the constraint is always binding in our policy scenarios). Our main interest is in the comparison between the scenarios BLACK&GREEN and BLACK.

Lignite (soft coal) has the highest CO_2 emissions per kWh electricity produced, and we therefore term it the dirtiest technology. When the emission constraint is imposed, power production by lignite power plants decreases by 41 per cent if no additional green quota is in place. As one increases the share of green power, the adverse impacts of the carbon constraint on lignite power production declines. This is shown in Figure 1, which sketches the change in output of the dirtiest technology compared to the BLACK scenario. When the green quota is increased to 23 per cent, output from lignite power plants increases by 17 per cent, and is then only 31 per cent below the BASELINE level.

Figure 1. Percentage change in output of lignite power production in BLACK&GREEN compared to BLACK

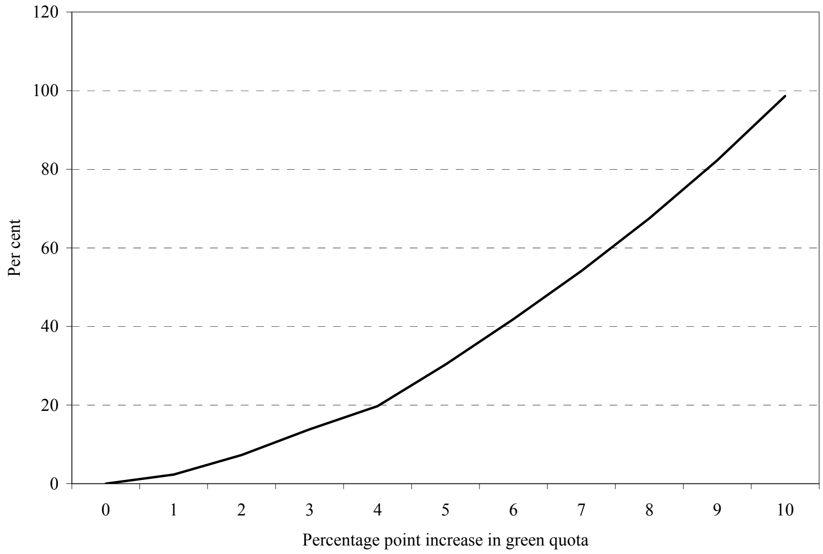


Imposition of a green quota on top of the black quota causes a substantial additional economic cost, cf. Figure 2. This must be considered as an excess burden if emission reduction is the only policy objective.[12] Without a green quota, the compliance cost of a 25 per cent cutback of emissions in the German electricity system amounts to roughly 1,100 Million Euros. With increasing shares of green power the cost rises up to around 2,200 Million Euros, i.e., compliance cost doubles when the green

[12] Alternatively, we may refer to the additional cost as a price tag that must be attached to the value of other potentially vague objectives such as decreased reliance on fossil fuels, improved technological progress etc. (see also footnote 5).

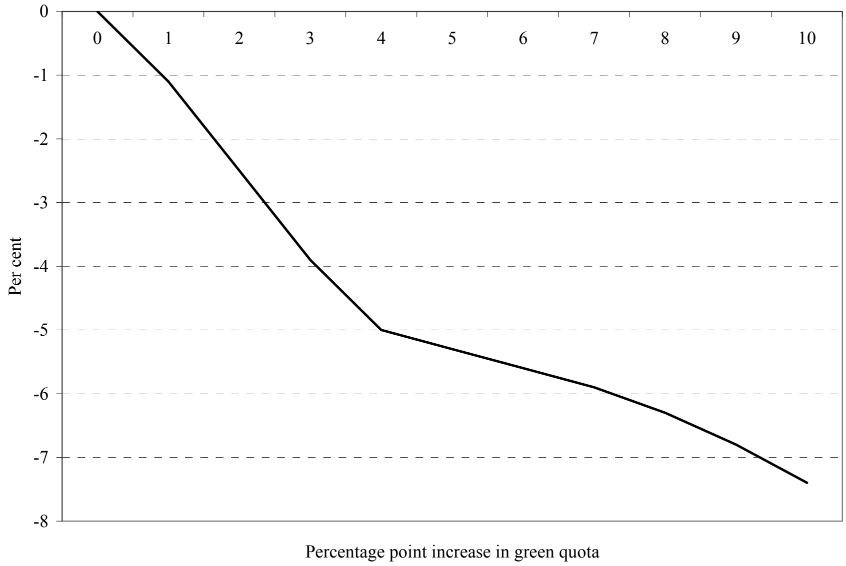
quota is increased by 10 percentage points. Compliance cost is calculated as loss in economic surplus, i.e., the sum of producer surplus, consumer surplus and CO_2 quota revenues.

Figure 2. Percentage change in compliance cost in BLACK&GREEN compared to BLACK



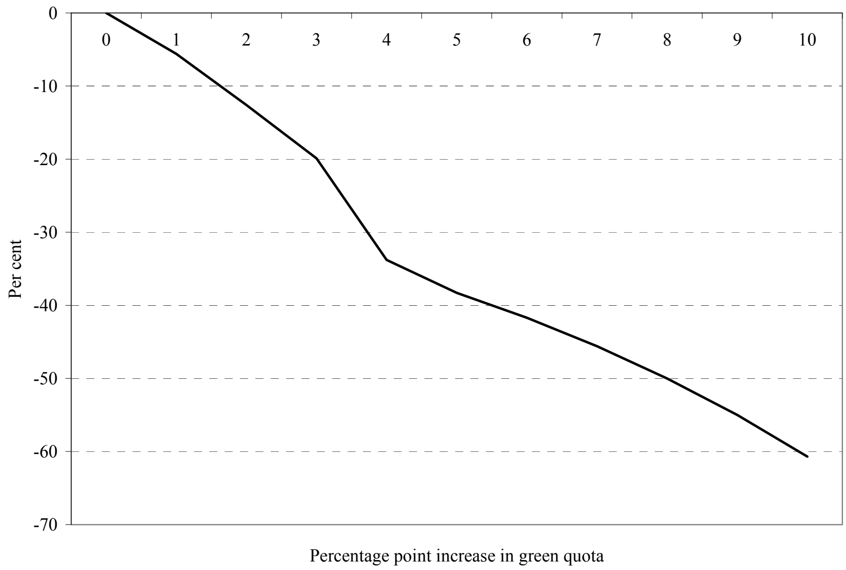
The end-user price of electricity increases by 12 per cent when the emission constraint is introduced. When the green quota is also imposed, the price declines quite substantially, and is then only 4 per cent higher than the BASELINE level (cf. Figure 3). In other words: Imposition of an additional green quota leads to increased electricity demand/production as compared to the BLACK scenario. As mentioned in the theoretical section, the price effect of introducing a green quota is in general ambiguous, but the likelihood of a price reduction is higher than in the case without any emission constraint in place.

Figure 3. Percentage change in end-user price of electricity in BLACK&GREEN compared to BLACK



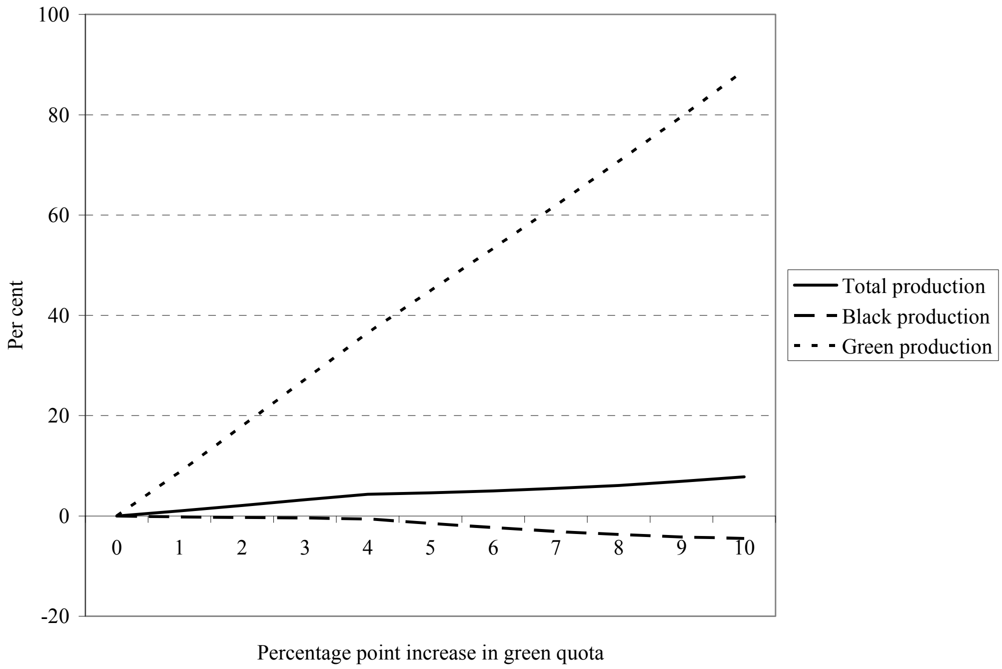
The price of CO_2 is 20 € per ton of CO_2 in the BLACK scenario, but is depressed to 8 € per ton when the green quota is also imposed, cf. Figure 4. This explains why the profitability of lignite power production increases in the BLACK&GREEN scenario.

Figure 4. Percentage change in CO_2 price in BLACK&GREEN compared to BLACK



Consistent with reduced end-user prices, total electricity production increases in BLACK&GREEN compared to the BLACK scenario. This is depicted in Figure 5, which also shows that total black production falls and total green production rises. Production of gas power, which is black but with relatively low emissions, is almost halved when the green quota is increased by 10 percentage points.

Figure 5. Percentage change in electricity production in BLACK&GREEN compared to BLACK



The figures above visualize the effects of increasing the green quota, given a fixed emission constraint of 25 per cent below BASELINE emissions. Figures 6 and 7 show respectively the relative changes in lignite production compared to BASELINE and the absolute loss in economic surplus of imposing different combinations of emission constraint and green quota. Note that the green quota in the figures should be read as *n* percentage points increase in the share of green power production compared to a scenario with the same emission constraint but no green quota.

Figure 6. Percentage change in lignite power production compared to BASELINE

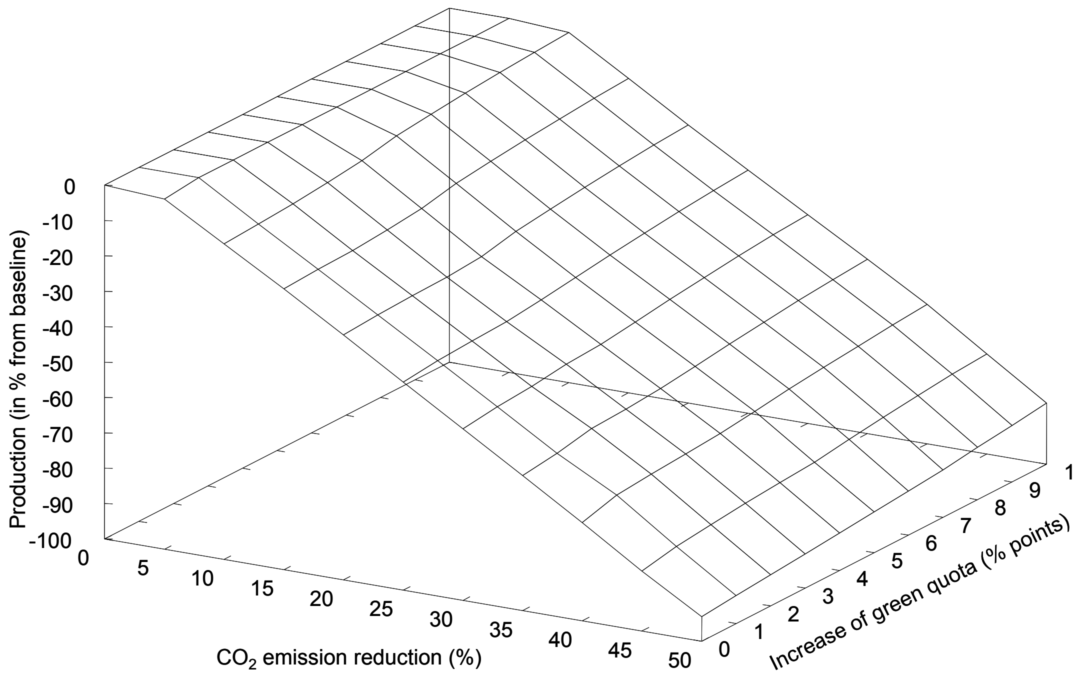
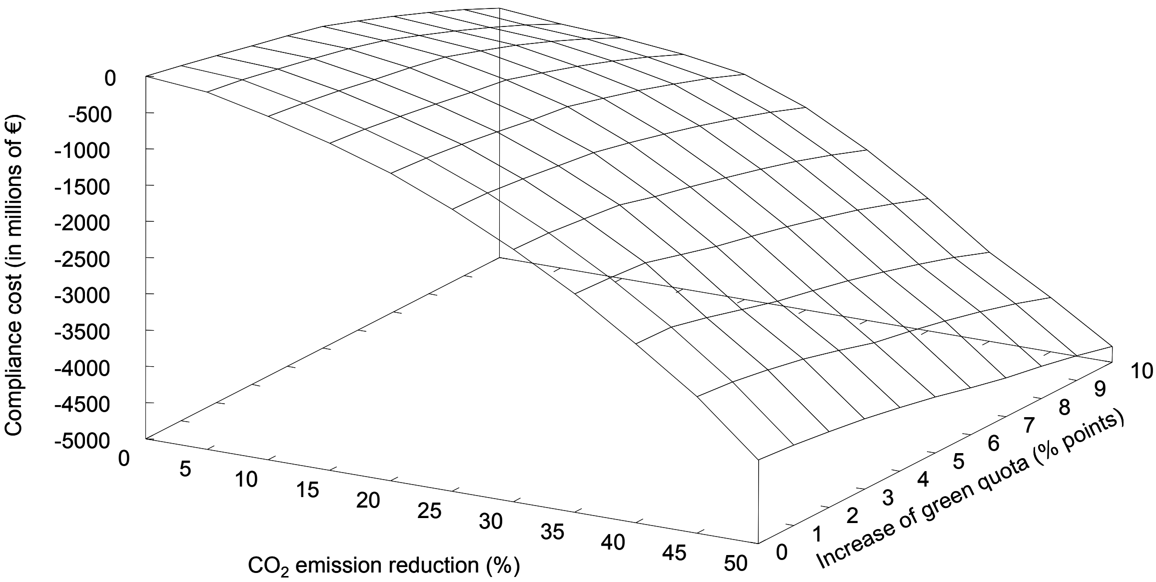


Figure 6 confirms the conclusions above, i.e., that introducing and increasing a green quota consistently raises the output of lignite power production, as long as a binding emission constraint is held constant. Increasing the emission constraint obviously has the opposite effect.

Figure 7 shows that the compliance cost of reaching an emission target increases with the stringency of the emission target, but also with the green quota. That is, there is significant excess cost of introducing a binding green quota on top of the emission constraint if the only goal is to reduce emissions of CO_2.

Figure 7. Compliance cost compared to BASELINE. Million Euros



5. Conclusions

Tradable black (CO_2) and green (renewables) quotas are introduced or proposed in many OECD countries. In this paper we have analyzed theoretically and numerically the economic implications of introducing a green quota on top of a black quota.

We find that, although the green quota further decreases total black power production, the dirtiest technology will actually gain. The reason is that the green quota reduces the shadow cost of the emission constraint, mainly benefiting the most emission-intensive technologies. Because some black producers must increase their production as long as the emission constraint is binding, one effect of the green quota is to serve the dirtiest technology. This result may have important implications for the policy debate on green quotas, and is perhaps what green protagonists do not know or want to know. Furthermore, our numerical simulations of the German electricity market show that the excess cost of imposing a green quota can be quite substantial. In other words, the price tag on green quotas for the composite of objectives different from emission reduction is large.

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Appendix 1

In this appendix we will show the equivalence of TGC markets and uniform feed-in tariffs financed by an end-user tax, and derive some more results that are specific to this choice of policy scheme. We use the same basic model as in Section 2, and start by modeling a TGC market with producer obligations. This means that green power producers are allowed to issue one certificate per unit of green power production, whereas black power producers are required to buy a certain number β of certificates for each unit of black power production.[13]

Equations (1) and (2) can then be specified as follows:

(A1) $$Max\left[p^E q^i - c^i(q^i) - \sigma a^i q^i - \beta\pi q^i\right] \quad (i \in B)$$

(A2) $$Max\left[p^E q^i - c^i(q^i) + \pi q^i\right] \quad (i \in G).$$

First-order conditions (3) and (4) become:

(A3) $$c^i_{q^i}(q^i) = p^E - a^i\sigma - \beta\pi \quad (i \in B)$$

(A4) $$c^i_{q^i}(q^i) = p^E + \pi \quad (i \in G).$$

In order to show that TGC is equivalent to a uniform feed-in tariff financed by an end-user tax, let the end-user tax be given by $\tau = \beta\pi$ and the feed-in tariff by $\pi^* = \pi + \tau = \pi(1 + \beta)$. We see from equations (A1) and (A2) that the maximization problems for black and green producers are the same under the two schemes. Moreover, tax income equals $\tau q = \beta\pi q$, whereas feed-in tariff expenditures equal $\pi^* q^G = \pi(1 + \beta)\alpha q = \pi(1 + \beta)(\beta/(1+\beta))q = \beta\pi q$. Thus, the two policy schemes are equivalent.

Equations (5) – (7) now become (note that $\pi = 0$ initially):

(A5) $$c^i_{q^i q^i}(q^i)dq^i = dp^E - a^i d\sigma - \beta d\pi \quad (i \in B) \quad (i \in B)$$

(A6) $$c^i_{q^i q^i}(q^i)dq^i = dp^E + d\pi \quad (i \in G).$$

(A7) $$\sum_{i\in B}\left(c^i_{q^i q^i}(q^i)\left(dq^i\right)^2\right) = dp^E\sum_{i\in B}dq^i + \sum_{i\in B}a^i dq^i - \beta d\pi\sum_{i\in B}dq^i = \left(dp^E - \beta d\pi\right)dq^B$$

From equation (A6) we have that either $dq^i > 0$ for all $i \in G$, or $dp^E < 0$ (or both). However, $dp^E < 0$ implies that $dq^G > 0$ (from the demand side), and hence we must have $dq^i > 0$ for all $i \in G$.

[13] This measure ensures that green power production constitutes $\alpha = \beta/(1+\beta)$ of total power production.

The effect on the electricity price is in general ambiguous, and depends on the parameters of the model; not least the cost functions of the different power producers and the emission intensities of black producers. We have from equations (A6) and (A7) that $(-d\pi) < dp^E < \beta d\pi$. An example of declining prices is obtained by assuming $a^i = a^j$ for all i, j. Then $dq^i = 0$ for all $i \in B$, and so we must have $dq > 0$ and thus $dp^E < 0$. An example of increasing prices is obtained in the following way: Assume that $a^i = 0$ for m identical black producers (e.g., nuclear), and $a^j = \tilde{a} > 0$ for the other black producers. Then q^j is unchanged due to the emission constraint. Assume further that there are $n = m$ identical green producers (labeled g), and that $c^i_{qq} < \beta c^g_{qq}$. From equations (A5) and (A6) we see that we must either have $dp^E > 0$, or $(-dq^i) > dq^G$. However, in the latter case we get $dq < 0$, and so $dp^E > 0$. Thus, the end-user price must increase.

Appendix 2

In this appendix we present the algebraic formulation of our numerical electricity market model. Table A1 depicts the notations for sets, parameters and variables underlying the model. We then provide a summary of the economic equilibrium conditions. Complementarity between equilibrium conditions and decision variables of the model are indicated by means of the " $\perp$ "-operator.

Table A1: Sets, variables and parameters

Sets:	
I	Set of all generation technologies (with index $i \in I$)
XT(I)	Subset of extant technologies (with index $xt \in XT \subset I$)
NT(I)	Subset of new vintage technologies (with index $nt \in NT \subset I$)
$R(I)$	Subset of renewable technologies (with index $r \in R \subset I$)
L	Set of load types (with index $l \in L$)

Table A1 (cont.)

Parameters:	
$\bar{y}_i$	Base-year electricity output by technology *i* (TWh)
$\bar{s}_l$	Base-year electricity supply by load *l* (TWh)
$\bar{s}_i^l$	Base-year electricity load supply by new vintage technology (TWh)
$\bar{z}$	Base-year aggregate domestic electricity supply (TWh)
$\bar{x}$	Base-year electricity exports (TWh)
$\bar{m}$	Base-year electricity imports (TWh)
$\bar{d}$	Base-year final demand of electricity (TWh)
$\bar{p}_i$	Base-year output price for power generation by technology *i* (Cent/KWh)
$\bar{p}_l$	Base-year load-specific price of electricity (Cent/KWh)
$\bar{p}$	Base-year consumer price of electricity (Cent/KWh)
$\bar{p}_{Int}$	International electricity price (Cent/KWh)
t	Electricity taxes and fees (Cent/KWh) ($\bar{t}$:= base-year taxes and fees)
g	Electricity grid fee (Cent/KWh) ($\bar{g}$:= base-year grid fee)
c_i	Per-unit cost of electricity production by technology *i* (Cent/KWh)
$co2_i$	Per-unit CO_2 emissions of electricity production by technology i (kg/KWh)
θ_i^l	Base-year value share of technology *i* supply in total domestic load supply
θ_l	Base-year value share of load supply *l* in aggregate domestic electricity supply
σ	Elasticity of substitution across different loads
σ_l	Elasticity of substitution across extant technologies entering load *l*
η	Price elasticity of electricity final demand
ε^X	Elasticity of export demand
ε^M	Elasticity of import supply
$\hat{y}_i$	Upper capacity limit on electricity production by technology *i* (TWh)
$\overline{co2}$	Mandated CO_2 emission limit – black quota (Mt CO_2)
r	Mandated minimum share of renewable electricity in final electricity demand – green quota
Activity levels:	
y_i	Electricity output by technology *i* (TWh)
s_l	Electricity supply by load *l* (TWh)
s_i^l	Electricity load supply by new vintage technology $i \in NT$ (TWh)
z	Aggregate domestic electricity supply (TWh)
x	Electricity exports (TWh)
m	Electricity imports (TWh)

Table A1 (cont.)

Price variables:	
p_i	Output price for power generation by technology *i* (Cent/KWh)
p_l	Load-specific price of electricity (Cent/KWh)
p	Consumer price of electricity (Cent/KWh)
p_{co2}	CO_2 price (Euro/t)
p_r	Price premium for renewable energy (Cent/KWh)
μ_i	Scarcity rent on production capacity limit of technology *i* (Cent/KWh)

Zero-profit conditions

The zero-profit conditions for the model are as follows:

- Zero-profit conditions for electricity production by technology i $\left(\perp y_i\right)$:

$$c_i + \mu_i + p_{co2}\frac{co2_i}{10} - p_r\Big|_{i\in R} + \frac{r}{(1-r)}\Bigg|_{i\notin R} \geq p_i$$

- Zero-profit condition for load supply by new vintage technology $i \in NT$ $\left(\perp s_i^l\right)$:

$$p_i \geq \sum_{i\to l} p_l \quad i \in NT$$

- Zero-profit condition for load aggregation $\left(\perp s_l\right)$:

$$\left[\sum_i \theta_i^l \left(\frac{p_i}{\overline{p}_i}\right)^{(1-\sigma_l)}\right]^{\left(\frac{1}{1-\sigma_l}\right)} \geq \frac{p_l}{\overline{p}_l}$$

- Zero-profit condition for final demand supply $\left(\perp z\right)$:

$$\left[\sum_l \theta_l \left(\frac{\left(p_l + t + g\right)}{\left(\overline{p} + \overline{t} + \overline{g}\right)}\right)^{(1-\sigma)}\right]^{\left(\frac{1}{1-\sigma}\right)} \geq \frac{p}{\overline{p}}$$

- Zero-profit condition for electricity imports $(\perp m)$:

$$m \geq \bar{m}\left[\frac{\left(p-\frac{r}{1-r}p^{r}\right)\bar{p}_{Int}}{\bar{p}}\right]^{\varepsilon^{M}}$$

- Zero-profit condition for electricity exports $(\perp x)$:

$$x \geq \bar{x}\left[\frac{\left(p-\frac{r}{1-r}p^{r}\right)\bar{p}_{Int}}{\bar{p}}\right]^{-\varepsilon^{X}}$$

Market-clearance conditions:

The market-clearance conditions for the model are as follows:

- Market-clearance condition for electricity generated by technology i $(\perp p_i)$:

$$y_i \geq \bar{y}_i \sum_{\substack{l \\ i\to l}} s_l^l \left[\left(\frac{p_l}{\bar{p}_l}\frac{\bar{p}_i}{p_i}\right)\right]^{\sigma_l}\Bigg|_{i\in XT} + s_i^l\Big|_{i\in NT}$$

- Market-clearance condition for electricity load l $(\perp p_l)$:

$$s_l \bar{s}_l + \sum_{\substack{i\in NT \\ i\to l}} s_i^l \geq z\bar{s}_l\left[\frac{(p-t-g)}{(\bar{p}-t-g)}\frac{\bar{p}_l}{p_l}\right]^{\sigma}$$

- Market-clearance condition for final electricity $(\perp p)$:

$$z\bar{z} + m - x \geq \bar{d}\left(\frac{p}{\bar{p}}\right)^{\eta}$$

- Market-clearance condition for output capacity constraint by technology i $(\perp \mu_i)$:

$$\hat{y}_i \geq y_i$$

- Market-clearance condition for CO_2 emission constraint, i.e. the black quota $\left(\perp p^{CO2}\right)$:

$$\overline{co2} \geq \sum_i co2_i \, y_i$$

- Market-clearance condition for renewable energy share, i.e. the green quota $\left(\perp p^{R}\right)$:

$$\sum_{i \in R} y_i \geq r \, \overline{d} \left(\frac{p}{\overline{p}} \right)^{\eta}$$