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

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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.

JEL Code: D61, H21, H22, Q58.

Keywords: emissions trading, green quotas, overlapping regulation.

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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 % 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 primary energy consumption to 20 % by 2020.[2] The EU proposal specifies national renewable targets for each member state, which can be met by over-fulfillment 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 standards (RPS) (Neuhoff et al., 2008).[3] The US also aims to increase its share of renewable energy, and more than half of the US states have established an RPS or a state-mandated target for renewables.[4]

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 by the year 2020 a reduction in greenhouse gas emission of 20 % as compared to 1990 levels, a share of renewable energy sources in primary energy consumption of 20 %, and an increase of energy efficiency of 20 per cent.

[3] Feed-in tariffs are used in e.g. Germany, France and Spain, whereas TGCs are implemented in e.g. the UK and Sweden.

[4] See http://www.dsireusa.org.

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.[5] More generally, the latter could be seen as a price tag on green quotas for the composite of objectives different from emission reduction.[6]

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 (typically coal power) as compared to a black quota regulation alone: green serves the dirtiest. The policy implications of this shift in comparative advantage depend on the valuation of ancillary benefits or costs across carbon-emitting power technologies. For example, the shift may be undesirable if increased coal power production comes along with negative local externalities such as lower air quality and health damages. On the other hand, an increase in coal power production can be desirable under energy security considerations or structural (adjustment) policies if coal is produced domestically and competing gas is imported.

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 in particular the most emission-intensive technologies. Given total constant emissions under a black quota, some black producers must increase their output with an overlapping green quota – the combination of black and green quotas thus leads to higher output from the dirtiest technologies as compared to a black quota stand-alone. We substantiate our theoretical findings with a numerical analysis for the German power sector where we also quantify the implications of overlapping regulation on excess cost, carbon values and electricity prices.

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[5] 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.

[6] 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 made 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.

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 analytically 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 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 want to show that green quotas imposed on competitive power markets that are already subject to emission regulation through a black quota will lead to (i) a decrease in total black production, (ii) a decrease in output from black technologies with no emissions and black technologies with lowest positive emissions; and (iii) an increase in output from the most emission-intensive technologies.

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. Emissions e^i in each firm are proportional to production, i.e., $e^i = \gamma^i \cdot q^i$, where γ^i denotes the emission intensity of firm *i*.[7] There are no emissions from green power production, i.e., $\gamma^i = 0$ for $i \in G$ ($\gamma^i \geq 0$ for $i \in B$).[8] Let $p^E = D(q)$ ($D_q < 0$) denote the inverse demand function, where p^E is the end-user price of electricity.

With respect to our analysis of overlapping regulation, we assume that the government has introduced a cap $\hat{e}$ on total emissions from the power sector, i.e., $\Sigma(\gamma^i \cdot q^i) \leq \hat{e}$, implemented through an emission trading system (ETS) where σ denotes the associated emissions price.[9] We then want to examine the

[7] This assumption reflects technical and physical restrictions in power production, where each power plant has a fairly fixed conversion rate between energy input and electricity output (except in start-up periods). It thereby provides a straightforward interpretation of the term 'dirtiest technology'. Below we will briefly discuss the implications of having a more general cost function $c^i(e^i, q^i)$.

[8] Note that some black producers, such as nuclear power plants, may have zero emissions.

[9] If the cap applies to the joint emissions from several sectors, including the power sector, result i) and ii) still hold but not necessarily iii). However, as emissions from the power sector are considered much more price sensitive than emissions from

effects of imposing (or strengthening) a green quota in the power market, which requires at least the share α of total power production to be covered from green power. The green quota could be thereby implemented in different ways, e.g., via tradable green certificates (TGCs), or via uniform or differentiated feed-in tariffs, possibly combined with an end-user tax (this is e.g. the regulatory practice in Germany). In our analysis we consider the latter case, i.e., a combination of technology-specific production subsidies to green producers (π^i) and a tax on electricity consumption (t). In Appendix 1 we show that TGCs can be represented as a special case of this policy combination, implying that our results also hold under TGCs. We assume that both the cap on emissions and the green quota are binding whenever they are imposed. Finally, we assume that $dt \geq 0$, i.e., the tax on consumption is not *reduced* as part of the policy to increase α.[10]

The maximization problem of black and green producers can be stated as:

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

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

First-order conditions are then:

(3) $$c^i_{q^i}(q^i) = p^E - t - \sigma\gamma^i \quad \left(i \in B\right)$$

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

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

(5) $$c^i_{q^i q^i}(q^i)dq^i = dp^E - dt - \gamma^i d\sigma \quad \left(i \in B\right)$$

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

We examine the case where the green quota α is increased marginally (by adjusting π^i and t). Because of the binding emission constraint, total emissions remain unaffected, i.e. $\sum\gamma^i \cdot dq^i = 0$. Thus, if one black producer with $\gamma^i > 0$ reduces output, some other black producer with $\gamma^i > 0$ must increase output. Multiplying equation (5) by dq^i and then summing up over all $i \in B$ we obtain:

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other sectors, result iii) will likely hold true in most relevant cases. Emitters outside the power sector will benefit from a green quota in the power sector.

[10] Although this assumption seems reasonable, we return to this below. It is straightforward to show that our results also hold in the presence of initial taxes or subsidies on black production, assuming that these taxes are not reduced (or subsidies not increased) as part of the new policy implemented to reach the green target. This assumption also seems reasonable.

(7) $$\sum_{i\in B}\left(c^i_{q^iq^i}(q^i)\left(dq^i\right)^2\right) = (dp^E - dt)\sum_{i\in B} dq^i + \sum_{i\in B}\gamma^i dq^i = (dp^E - dt)dq^B .$$

Assume that $\gamma^i \neq \gamma^j$ for at least one pair (i,j), which implies that $dq^i \neq 0$ for at least one i.[11] The left-hand side of equation (7) is then strictly positive, which means that dq^B and $(dp^E - dt)$ must have the same sign (and differ from zero). If $(dp^E - dt) > 0$ and $dq^B > 0$, then $dp^E > 0$ (since $dt \geq 0$) and $dq > 0$ (since α increases), which is inconsistent with the demand function. Consequently, we must have $dq^B < 0$ and $(dp^E - dt) < 0$. Equation (5) then implies that $d\sigma < 0$, because otherwise we would have $dq^i < 0$ for all $i \in B$. Furthermore, let γ^* be defined so that $dp^E - dt - \gamma^* d\sigma = 0$. Then we have from equation (5) that $dq^i < 0$ for all black firms with $\gamma^i < \gamma^*$, and $dq^i > 0$ for all firms with $\gamma^i > \gamma^*$. In other words, the dirtiest technologies increase their production, whereas the least dirty black technologies decrease their output. Moreover, not only will any black producer with $\gamma^i = 0$ (e.g., nuclear power) reduce its output, but the black producer with lowest $\gamma^i > 0$ (typically gas power) will also reduce its output (otherwise total emissions would rise).[12]

How can we intuitively explain our central analytical finding that output from the most emission-intensive power producers increase when the green quota is imposed or strengthened? 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 cap, the second-order effect is a reduction in the price of emissions. This benefits in particular the most emission-intensive technologies. As compared to a black quota stand-alone, overlapping regulation leads to higher output from the dirtiest technologies. This result is in sharp contrast to the case where there is no emission quota in place, in which case all black producers reduce their output (see e.g. Fischer, 2006).

Our results hold for a range of policy instruments that promote green power production. Beyond green producers' subsidies (possibly combined with higher taxes on electricity consumption) or tradable green certificates (TGC), the basic economic mechanisms apply to any policy (e.g., research stimulus) that reduces the marginal costs of producing green power (or other emissions-free power such as

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[11] The implication can be shown as follows: If $dq^i = 0$ for all $i \in B$, equation (5) tells us that we must either have $\gamma^i = \gamma^j$ for all i, j, or $d\sigma = 0$. However, $d\sigma = 0$ and $dq^i = 0$ implies that $dp^E = dt \geq 0$, which (from the demand side) is impossible because we have $dq > 0$ whenever $dq^B = 0$ and the share of green production α is increased. Thus, $dq^i = 0$ for all $i \in B$ must imply $\gamma^i = \gamma^j$ for all i, j, in which case there is no meaning in the term 'dirtiest' black technology.

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

nuclear):[13] By increasing the profitability of emissions-free technologies, the cap on emissions is more easily achieved; this results in a lower emissions price, benefiting the most emissions-intensive technologies.

The effects on the end-user price of electricity and green power production will depend on the specific implementation of green quotas In Appendix 1 we show that TGC markets and uniform feed-in tariffs financed by an end-user tax on electricity consumption are equivalent, and will both increase output from all green power producers. The end-user price of electricity can either increase or decrease in the case with TGC (cf. Appendix 1).[14] 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 a binding emission quota is already in place, since the reduced emissions price has a stimulating effect on black production. Nevertheless, an increase of the electricity price can occur if the black producers have very different emission intensities, and the green producers have much steeper marginal production cost than the least emission-intensive black producers.

Many 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). This result is straightforward by economic intuition and easy to show in analytical terms. From a regulatory policy perspective, however, the crucial question remains how large this excess cost is, constituting an implicit price tag for other potential benefits of greener power production (e.g., enhanced energy security and technological progress). In the numerical analysis below we assess the magnitude of the excess cost of overlapping regulation, and leave it up to policy makers to trade off excess cost with potential benefits.

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[13] The results do not hold if the green power stimulus is combined with a very generous reduction in the consumer tax t, in which case demand for electricity could be stimulated so much as to *increase* the producer price of black producers and hence the price of emissions.

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

3. Numerical framework

In order to quantify the implications of overlapping green and black quotas and thereby assess the policy relevance of our theoretical analysis we perform numerical simulations with 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 associated to base, middle, or peak load. The different load supplies are then combined towards a constant-elasticity-of-substitution aggregate of domestic electricity supply. After accounting for taxes and grid fees the domestic electricity supply together with net imports must satisfy price-responsive 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 recent official energy data sources 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).

The electricity market model is formulated as a mixed complementarity problem (MCP), i.e. a system of (weak) inequalities and complementary slackness conditions (see e.g. Rutherford (1995)).[15] 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.

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 policy background 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 % below 1990 levels by 2020. It has also adopted the target of increasing the share of renewables in total energy use to 20 % 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 % from 1990 levels. Beyond the 1st commitment period, Germany will pursue more stringent emission cutbacks until 2020 (in fact up to 40 % from 1990 emission levels) and increase the share of renewable energies in power production up to 30 %. Against this policy background we illustrate the implications of overlapping black and green quotas for the German electricity market taking a 25 % 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 % below BASELINE emission level	Not assigned
BLACK&GREEN	25 % below BASELINE emission level	n percentage points increase compared to BLACK, $n \in \{1,10\}$

[15] 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), Takayma and Judge (1971) or Böhringer and Rutherford (2008)) which are inherent to economic models formulated as optimization problem.

With the emission constraint in place under scenario BLACK, the share of green power production endogenously increases from 11 to 13 %. Thus, in scenario BLACK&GREEN the share of green power production is imposed to go up from 13 to 23 %, 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 % if no additional green quota is in place (scenario BLACK). When policy regulation requires the share of green power to increase further beyond the level obtained in scenario BLACK, the adverse impacts of the carbon constraint on lignite power production declines (scenario BLACK&GREEN). 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 reaching 23 %, output from lignite power plants increases by 17 %, as compared to BLACK, and is then only 31 % below the BASELINE level.

As sketched in Figure 2, imposition of a green quota on top of the black quota causes a substantial additional economic cost. This must be considered as an excess burden if emission reduction is the only policy objective.[16] Without a green quota, the compliance cost of a 25 % cutback of emissions in the German electricity system amounts to roughly 1.1 billion Euros. With increasing shares of green power the cost rises up to around 2.2 billion Euros, i.e., compliance cost doubles when the green quota is increased by 10 percentage points (note that compliance cost is calculated as loss in economic surplus, i.e., the sum of producer surplus, consumer surplus and quota revenues).

The end-user price of electricity increases by around 12 % for the emission quota stand-alone (scenario BLACK). When the green quota is imposed on top of the black quota, the price declines markedly, and is then only 4 % higher than the BASELINE price (cf. Figure 3); imposition of an additional green quota leads to increased electricity demand/production as compared to the BLACK scenario.[17] The price of CO_2 is 20 € per ton of CO_2 in the BLACK scenario, but declines 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.

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[16] 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.

[17] As mentioned in section 2, 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 1: Percentage change in output of lignite power production in BLACK&GREEN compared to BLACK

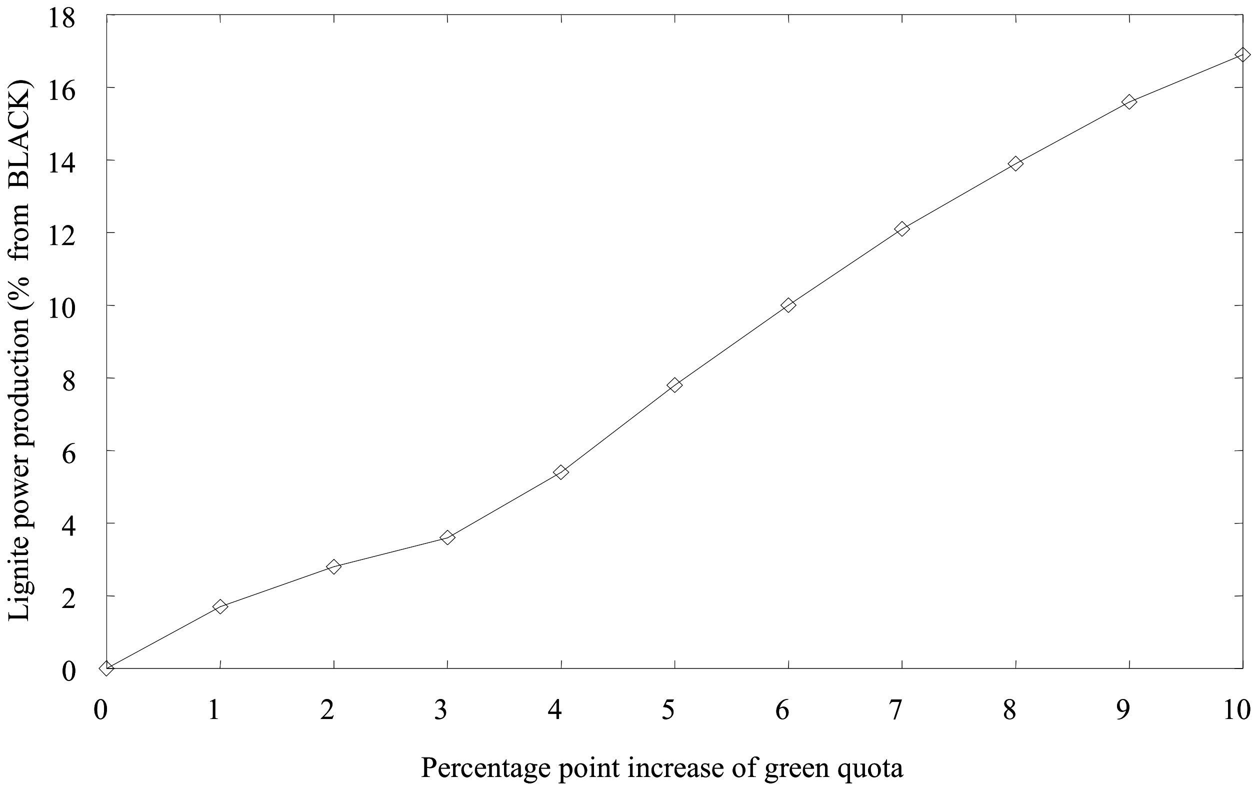


Figure 2: Percentage change in compliance cost in BLACK&GREEN compared to BLACK

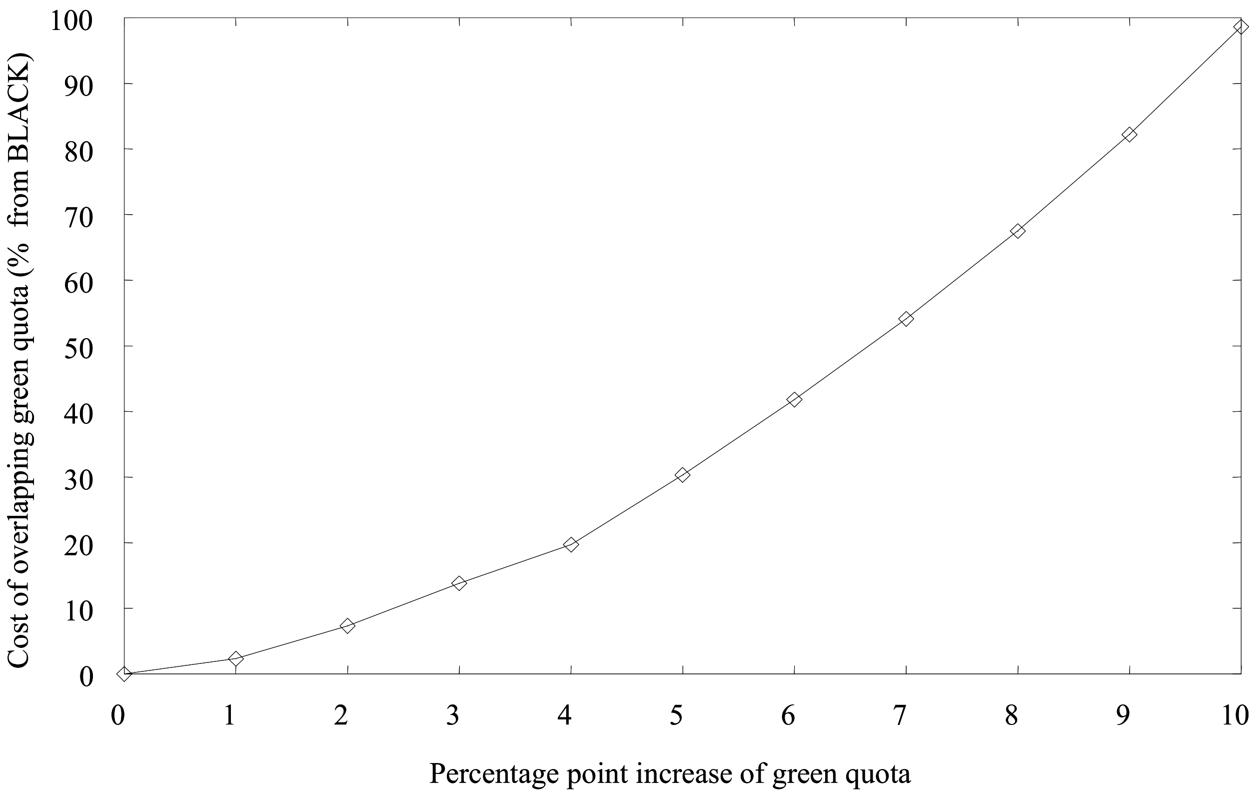


Figure 3: Percentage change in end-user price of electricity in BLACK&GREEN compared to BLACK

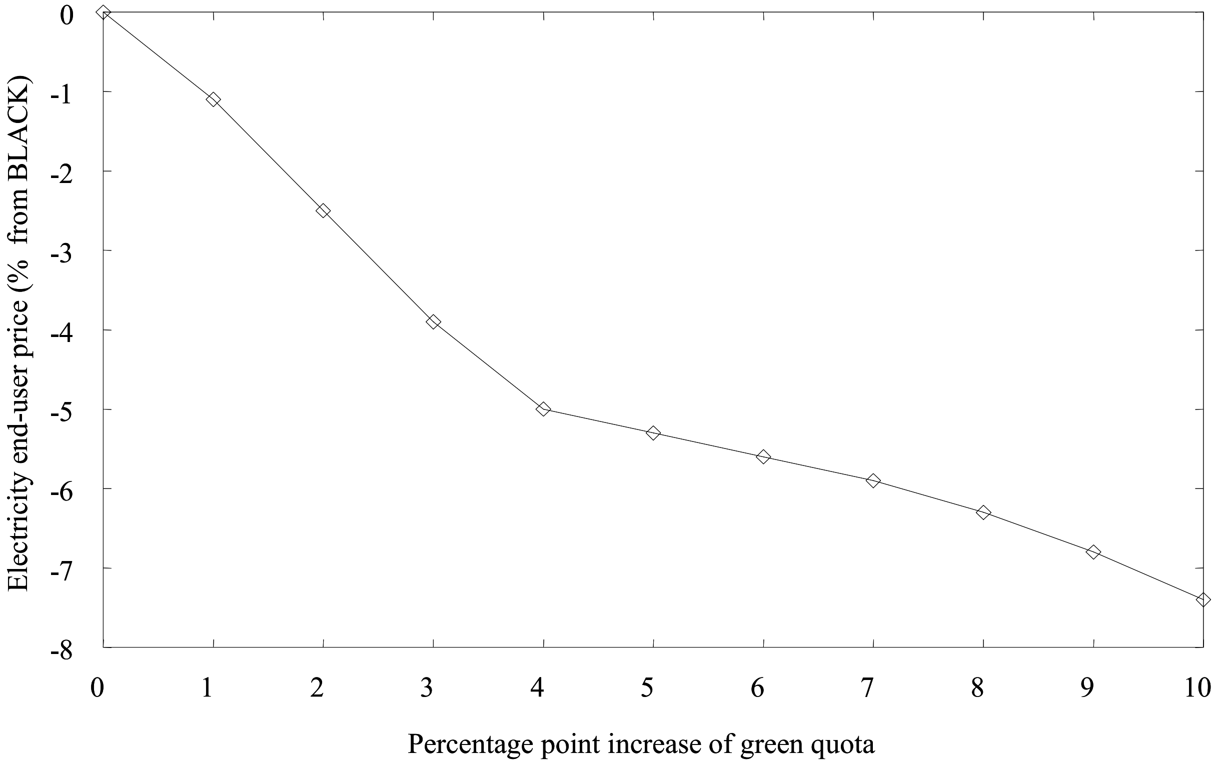
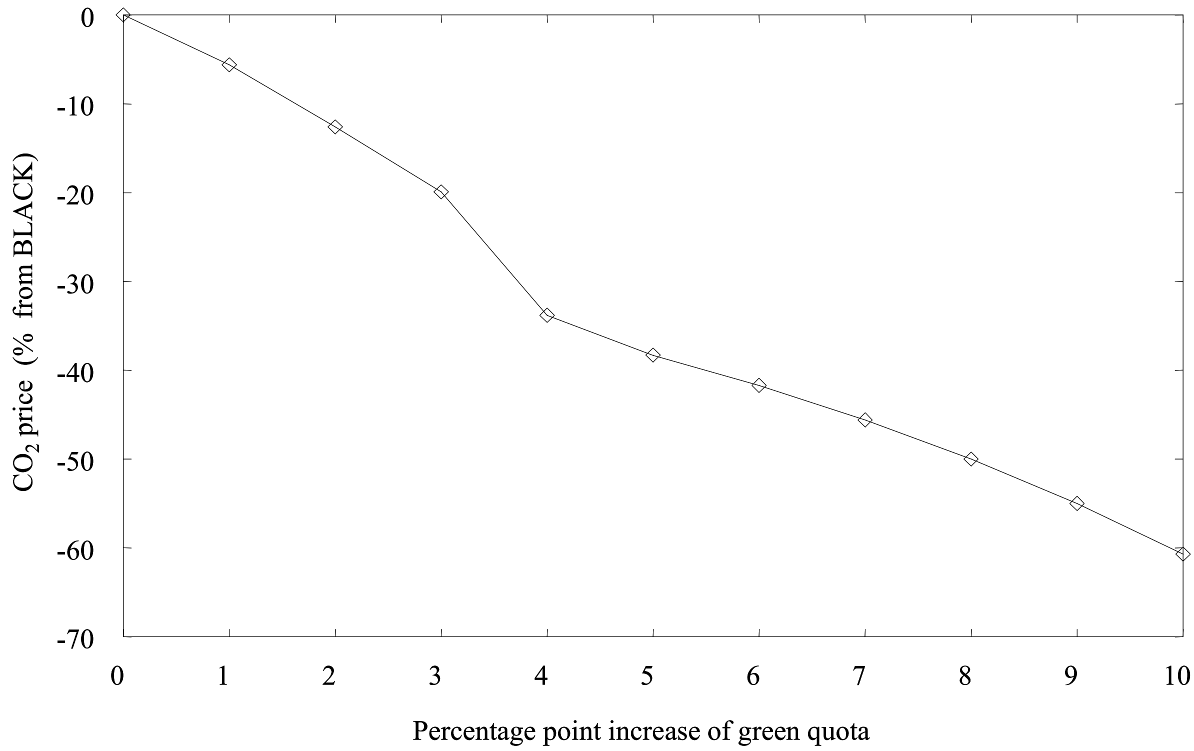
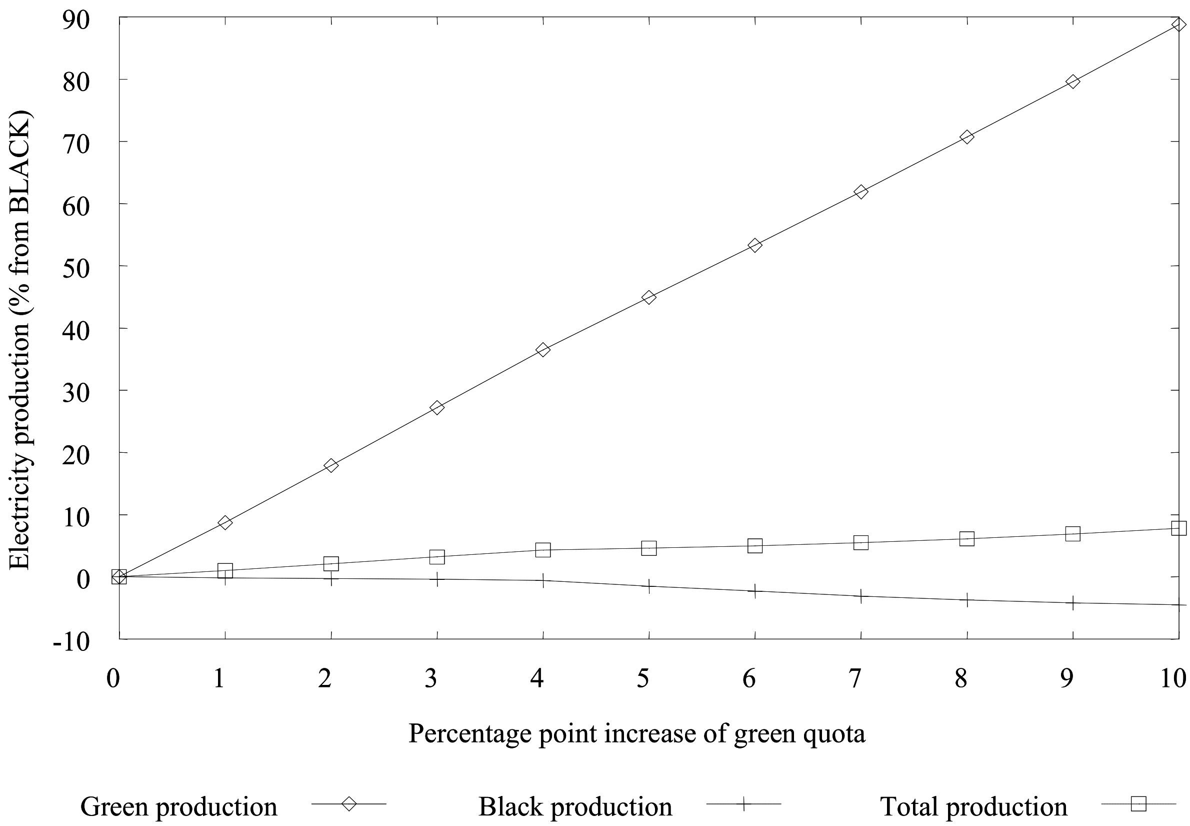


Figure 4: Percentage change in CO_2 price in BLACK&GREEN compared to BLACK



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



So far, we have quantified the effects of an overlapping green quota for a fixed emission constraint of 25 % below BASELINE emissions. Figures 6 and 7 provide some sensitivity analysis for alternative emission reduction targets (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 confirms our previous conclusion that introducing and increasing a green quota 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 6: Percentage change in lignite power production compared to BASELINE

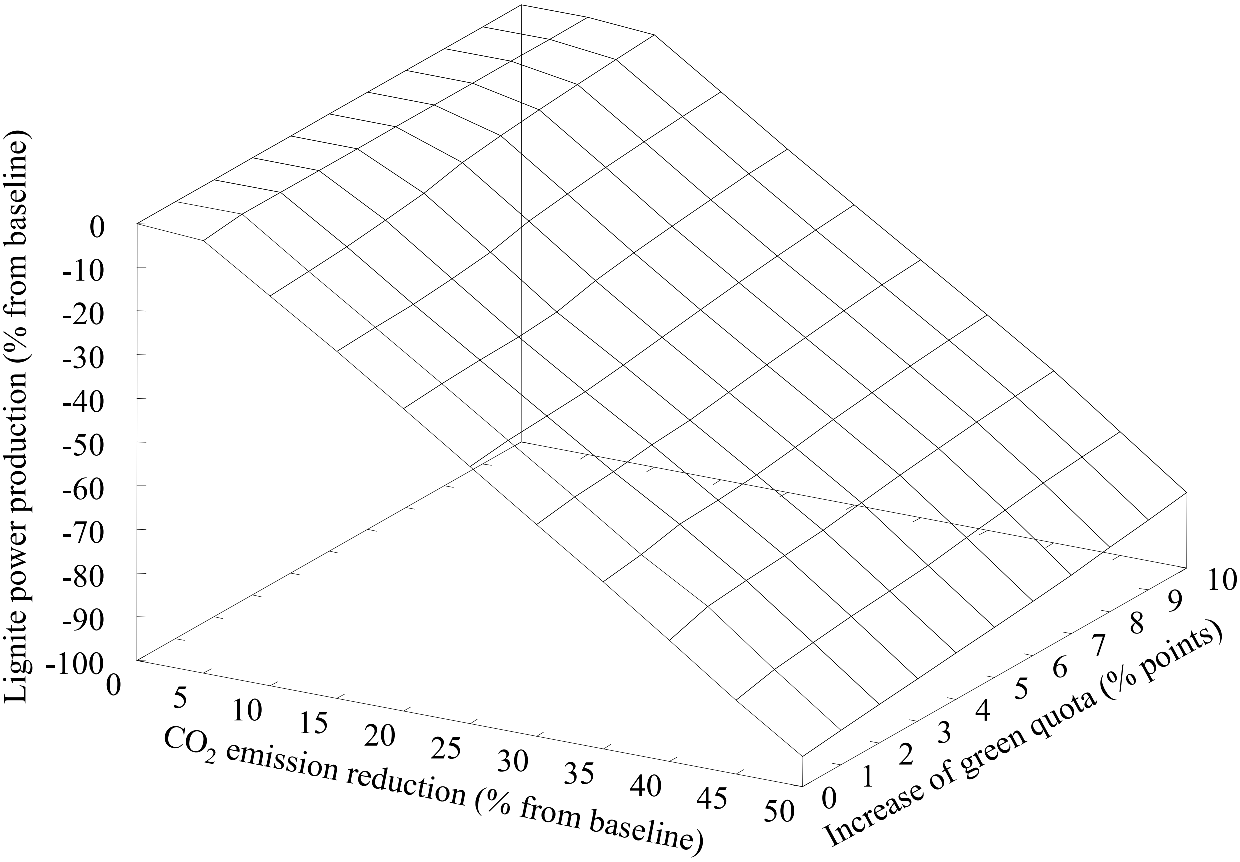
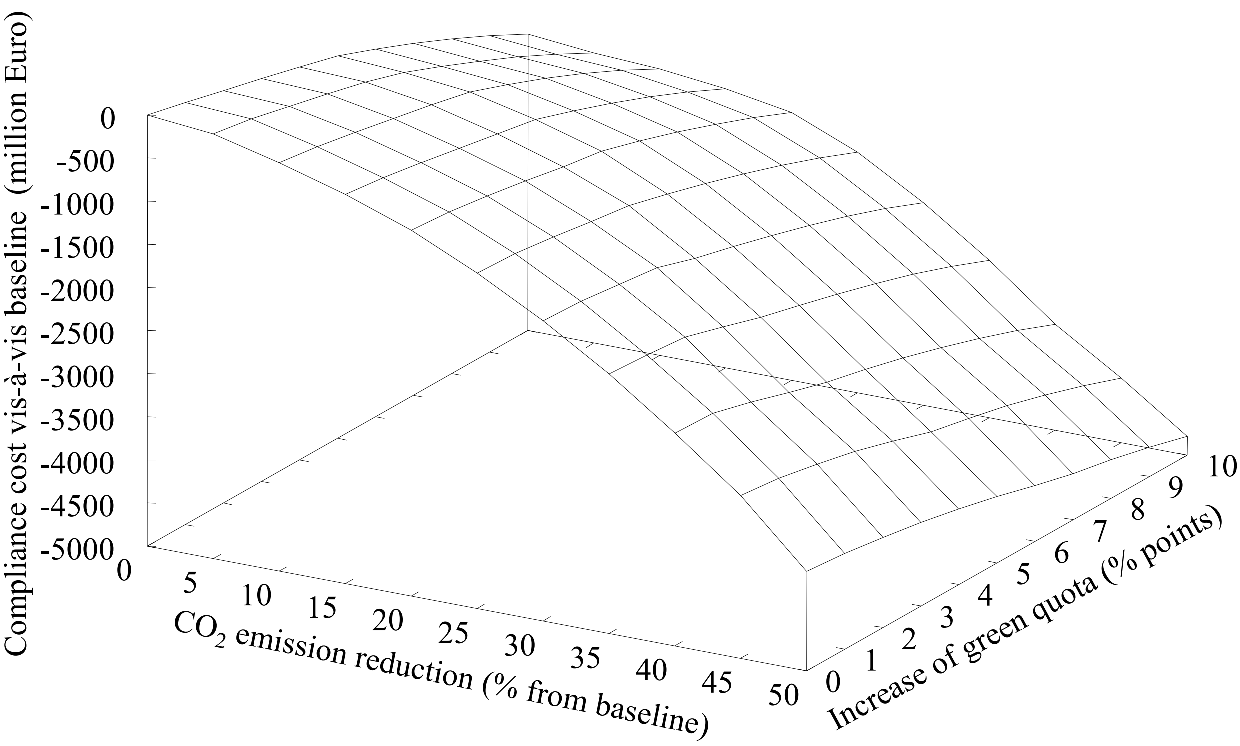


Figure 7: Compliance cost compared to BASELINE (in million Euros)



5. Conclusions

Tradable black (CO_2) and green (renewables) quotas are introduced or proposed in many OECD countries In this paper we have investigated the economic implications of introducing a green quota on top of a black quota – both from a theoretical perspective as well as in empirical terms using real-world data.

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. The insight that an overlapping green quota serves the dirtiest technology may have important policy implications depending on the induced cost and benefits for different interest groups or more generally the trade-offs between competing policy objectives. Our quantitative results for the German electricity market show furthermore that the additional cost of imposing a green quota can be quite substantial. To put it differently: The price tag on green quotas for the composite of objectives different from emission reduction is large and thus calls for an explicit and coherent policy justification.

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Appendix 1: Analytical derivations

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.[18]

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

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

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

(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 $t = \beta\pi$ and the feed-in tariff by $\pi^* = \pi + \tau = \pi(1 + \beta)$. We see from equations

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

(A1) and (A2) that the maximization problems for black and green producers are the same under the two schemes. Moreover, tax income equals $tq = \beta\pi q$, 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. In Section 2 we made the assumption that $t \geq 0$, which obviously holds here when β increases.

Equations (5) – (7) now become:

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

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

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

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 $i \in G$.

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 $(-d\pi) < dp^E < (\beta d\pi + \pi d\beta)$. An example of declining prices is obtained by assuming $\gamma^i = \gamma^j$ 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, where we assume that $\pi = 0$ initially: Assume that $\gamma^i = 0$ for m identical black producers (e.g., nuclear), and $\gamma^j = \tilde{\gamma} > 0$ 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: Algebraic Summary of Numerical Model

In this appendix we present the algebraic formulation of our numerical electricity market model. Tables A-C provide a summary of 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 A: 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 B: 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

Table C: Variables

Quantity variables:	
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)

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* $(\perp y_i)$:

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

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

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

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

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

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

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

- 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 $\left(\perp \mu_i\right)$:

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

-
- 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 $\left(\perp p^R\right)$:

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

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