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Greening Electricity More Than Necessary: On the Excess Cost of Overlapping Regulation in EU Climate Policy

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Abstract. After the failure of the United Nations climate change conference at Copenhagen the EU is under domestic pressure to justify ambitious unilateral emissions reduction targets. Cost efficiency of EU-wide emission abatement becomes increasingly important in order to sustain EU leadership in climate policy. We argue that administered EU targets for renewable energies are doomed to make emission reduction much more costly than necessary and therefore could rather hinder than promote public support to unilateral action.

Keywords: EU Climate Policy; Emission Quotas; Green Quotas; Overlapping Regulation

JEL classification: D61; H21; H22; Q58

1. Introduction

Since the early nineties the EU has pushed for climate protection at the international level. It has become a leader of the global climate policy agenda through its pivotal role in the ratification and implementation of the Kyoto Protocol, the sole international climate agreement to date with binding emission reduction targets for major industrialized countries. However, the latest United Nations climate change conference of parties (COP 15) at Copenhagen in December 2009 turned out to be a severe backslash to the EU's aspiration for winning "the battle against global climate change" (European Commission 2005, 2008a). In the run-up of COP 15 the EU had worked hard towards a Post-Kyoto treaty. As a distinct signal the EU had agreed on unilateral greenhouse gas emission reductions of at least 20% until 2020 (compared to 2005 emission levels) within the so-called EU Climate and Energy Package (European Commission 2008b). The EU's decision on leading the way with unilateral action was strongly motivated by the hope to foster a successful multilateral agreement at Copenhagen. However, instead of binding emission reduction commitments for major industrialized and developing regions, Copenhagen brought about only a voluntary system of pledge-and-review. After the failure of Copenhagen the EU is under increasing domestic pressure to relax its ambitious emissions reduction targets as various Central and Eastern European Member States had questioned the strictness of EU climate policy already beforehand. Major concerns refer to fears about substantial unilateral adjustment cost for the EU economy while non-EU regions take a free-ride, and the environmental impacts of EU emission reductions on global climate change will be rather negligible anyway.

Against this background cost efficiency of EU emission reduction will become increasingly important in order to sustain EU leadership in climate policy: If EU unilateral climate policy turns out to be excessively expensive, public support may critically decrease. Simple economic textbook analysis provides clear-cut guidance on how the EU can achieve its stated reduction target at minimum cost. Emission rights should be issued at the level of the targeted overall emission quantity and these rights then should be traded across *all* emission sources. The beauty of such a comprehensive cap-and-trade system is that no central planner information on specific abatement possibilities is required; the market will work out the least-cost solution by establishing a uniform emission price. In this case the marginal cost (price) to each use of a given pollutant is equalized, thereby assuring that the cheapest abatement options are realized. A fundamental feature of cost-efficient implementation is that only one policy instrument is required to meet the single policy target of emission reduction at least cost. This insight had been established in more general terms through the seminal work of Tinbergen (1952), which calls for the equalization of the number of instruments with the number of policy targets. While more targets than instruments make targets incompatible, more instruments than targets make instruments alternative (i.e. one instrument may be used instead of another or a combination of others).

However, contemporary EU climate policy violates basic principles of cost-effectiveness. Firstly, the EU Climate and Energy Package which is the central piece of legislation to achieve the overall EU emission reduction target, does not accommodate comprehensive EU-wide emission trading. The EU foresees explicit emission trading only between energy-intensive installations (sectors) under the EU Emissions Trading Scheme (EU ETS), which covers just around 40% of EU greenhouse gas emissions. Each EU Member State must therefore specify additional domestic abatement policies for the sectors outside the EU ETS in order to comply with the overall EU emission reduction objective through mandated country-specific targets for the non-ETS segments of its domestic economy.[1] Since there are no tight links between the ETS emission market on the one hand and the non-ETS emission "markets" on the other hand, the Coase theorem no longer applies. Thus, there is the threat of substantial excess cost as the initial allocation of abatement burden between ETS and non-ETS sectors will in general induce diverging marginal abatement cost (cf. Böhringer et al. 2005).[2]

Secondly – and not at least because of the fragmentation into one ETS market and twenty-seven domestic policy regimes for the non-ETS sectors – the EU employs a broader policy mix instead of one single instrument to meet its climate policy target. Beyond emissions trading the EU builds upon the explicit promotion of renewable energy production and energy efficiency both in ETS as well as non-ETS segments of the economy.[3] Efficiency and renewable targets have triggered a wide variety of policy measures across the 27 EU Member States including implicit or explicit subsidies to renewables, efficiency standards for buildings and specific product policies such as banning incandescent light bulbs or patio heaters. From the sole perspective of climate policy, the myriad of instruments used in the EU to curb greenhouse gas emissions is doomed to generate excess cost due to overlapping counterproductive regulation. If targets for renewable energy and energy efficiency become binding, they give an outcome different from the cost-effective solution generated by comprehensive emission trading and thereby create additional cost (cf. Böhringer et al. 2009).

This paper elaborates on the excess cost of EU climate policy induced by targets for renewable energies (green quota), which are imposed on a power market already regulated by an emission constraint (black quota). We first derive analytical results and then substantiate our theoretical findings with numerical simulations for the EU power sector, where we quantify the implications of overlapping green and black quotas for excess cost, electricity prices and electricity demand, emission prices as well as the power generation mix.[4] Our simulation results indicate substantial excess cost of emission reduction

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[1] More specifically, the targeted EU greenhouse gas reduction of 20% by 2020 (vis-à-vis 1990) is split between ETS and non-ETS segements of the EU economies as follows: From 2013 onwards the EU ETS sectors will be centrally regulated by the EU Commission to achieve a target reduction for this segment of -21% (compared to 2005) by 2020. Emissions outside the EU ETS are unregulated at the EU level, but subject to emissions control measures by individual Member States. The average reduction target for non-ETS greenhouse gas emissions until 2020 amounts to -10% (compared to 2005). Individual Member State targets for non-ETS sectors, however, range from a 20% decrease to a 20% increase relative to 2005 emission levels depending on differences in per-capita income.

[2] As pointed out by e.g. Neuhoff et al. (2006), allocation rules in the EU ETS have also led to distortions, causing diverging marginal abatement costs even among EU ETS installations. This problem will however be substantially reduced from 2013 when the power sector (with some exceptions) no longer will receive free allowances.

[3] The EU Climate and Energy Package includes a 20 % target share of renewable energy sources in gross final energy consumption and a mandated increase of energy efficiency of 20 % by 2020 along with the 20 % greenhouse gas emission reduction target.

[4] Similar numerical analyses, but with seemingly simpler modelling tools and somewhat different perspectives, have previously been undertaken for Spain (Linares et al., 2008) and Germany (Rathmann, 2007). An early theoretical study on

due to mandated target shares for renewable energy sources, which makes electricity production "greener" than necessary. In the conclusions we discuss whether objectives other than emission reductions (e.g., energy security and technological progress) can justify this considerable price tag on green quotas (European Commission, 2008b). We conclude that the relative contribution of renewables should be determined by markets, regulated by a suitable set of policy instruments, and not mandated by the EU.

2. Theoretical analysis

In our theoretical analysis we show that binding target shares for renewable energies (green quota) imposed on top of an emission constraint (black quota) will lead to excess cost of meeting the black quota. For the sake of simplicity, the formal analysis adopts a partial equilibrium approach but we also discuss the implications of overlapping regulation in an economy-wide context.

Following Böhringer and Rosendahl (2010) 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 $c^i_{qq} > 0$. 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.[5] There are no emissions from green power production, i.e., $\gamma^i = 0$ for $i \in G$. Black power producers may either have strictly positive emissions (i.e., those based on fossil fuels), or no emissions (e.g., nuclear), i.e., $\gamma^i \geq 0$ for $i \in B$. Let $p^E = D(q)$ ($D_q < 0$) denote the inverse demand function, where p^E is the end-user price of electricity.

We assume that the government wants to maximize economic welfare in the power market, subject to a cap $\hat{e}$ on total emissions from this sector (i.e., a black quota). Economic welfare consists of consumer and producer surplus, and net government revenues. Money transfers between consumers, producers and the government cancel out, and so the maximization problem becomes:

(1) $$\underset{q^i}{\text{Max}}\ W = \int_0^q D(s)ds - \sum_{i \in B,G} c^i(q^i),$$

subject to:

(2) $$\sum_{i \in B} \gamma^i q^i \leq \hat{e},$$

where $q = \sum_{i \in B,G} q^i$.

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interactions between black and green quotas is provided in Amundsen and Mortensen (2001). See also Böhringer and Rosendahl (2010) for an analytical contribution on this issue.

[5] 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).

This gives the following first-order conditions:

(3) $$\frac{\partial W}{\partial q^i} = D(q^i) - c^i_{q^i}(q^i) - \lambda q^i \Leftrightarrow p^E = c^i_{q^i}(q^i) + \lambda \gamma^i ,$$

where λ is the shadow price on the emission constraint in (2). It is straightforward to see that the welfare maximum can be reached by introducing an emissions trading system with $\hat{e}$ quotas (or a tax on emissions), in which case the first-order conditions for the firms become (σ is the price of quotas):

(4) $$p^E = c^i_{q^i}(q^i) + \sigma \gamma^i .$$

Obviously, as the total number of quota is set equal to $\hat{e}$, we will get $\sigma = \lambda$.

What happens to economic welfare if the government in addition implements a green quota through a suitable set of new instruments? By a green quota we mean a minimum share α of green power production in total power generation. If the green quota is binding, i.e., the share of green power in the welfare maximizing outcome is less than α, economic welfare will have to fall as the market outcome is moved away from this welfare maximizing outcome. Assume, for example, that the government introduces subsidies $\pi^i \geq 0$ to green producers and possibly a tax $t \geq 0$ on electricity consumption in order to implement the green quota.[6] The firms' first-order conditions are then:

(5) $$p^E = c^i_{q^i}(q^i) + t + \sigma \gamma^i \quad (i \in B)$$

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

Comparing (5)-(6) with (3), we see that the welfare maximum is no longer obtained unless we set $\pi^i = 0$ and $t = 0$, in which case the green quota will not be reached (by assumption).

The effects on total production and the end-user price of electricity of implementing the green quota are ambiguous as long as $t > 0$ (Böhringer and Rosendahl, 2010). Therefore, we first assume that p^E and q are unchanged, and focus on the welfare effects of shifting production between producers. Böhringer and Rosendahl (2010) show that the green quota will lead to higher production from the most emission-intensive technologies ($\gamma^i > \gamma^*$), and of course from the green technologies, and less production from the least emission-intensive technologies ($\gamma^i < \gamma^*$). The former effect follows because the price of emissions drops. The welfare loss will therefore equal the cost increases from higher production by green producers and the most emission-intensive black producers, minus the cost decreases from less production by the least emission-intensive black producers. In other words:

(7) $$\Delta W = \sum_{i \in G} \Delta c^i(q^i) + \sum_{i \in B, \gamma^i > \gamma^*} \Delta c^i(q^i) + \sum_{i \in B, \gamma^i < \gamma^*} \Delta c^i(q^i) ,$$

[6] Note that a green certificate market can be mimicked by a combination of a subsidy to green production and a tax on elecitricity consumption, where net public revenues from these instruments are zero (Böhringer and Rosendahl, 2010).

where the two first terms are positive and the third term is negative. Remember that in this case we have $\sum_{i \in G} \Delta q^i + \sum_{i \in B, \gamma^i > \gamma^*} \Delta q^i + \sum_{i \in B, \gamma^i < \gamma^*} \Delta q^i = 0$. This is illustrated in Figures 1a-c with two black producers and one green producer where emission intensity of black producer B_1 is twice as high as the emission intensity of black producer B_2 ($\gamma^{B1} = 2\gamma^{B2}$).

In this example the black producer B_1 and the green producer will increase their output by the same amount when we go from the Black (B) scenario to the Black&Green (B&G) scenario (i.e., impose a green quota in addition to the black quota), and hence black producer B_2 decreases its output by twice this amount so that total output is unchanged. The marginal cost of production (excluding emissions cost) for B_2 are initially equal to the average marginal cost of production for B_1 and G (cf. (4) with $\gamma^{B1} = 2\gamma^{B2}$), and thus we get a deadweight loss by shifting some production from B_2 to B_1 and G.[7] The total welfare (deadweight) loss is illustrated as the sum of the three triangles in the three figures.

Figure 1a.: B_1 production in Black (B) and Black&Green (B&G) scenarios

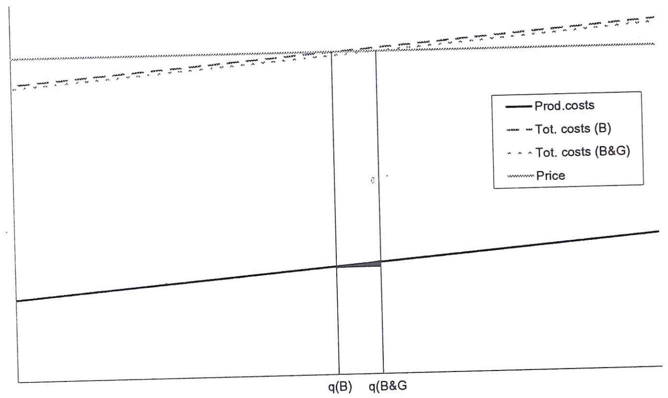


Figure 1b.: B_2 production in Black (B) and Black&Green (B&G) scenarios

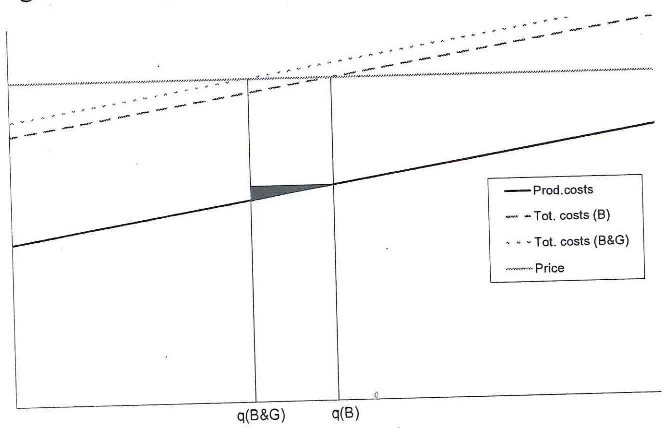
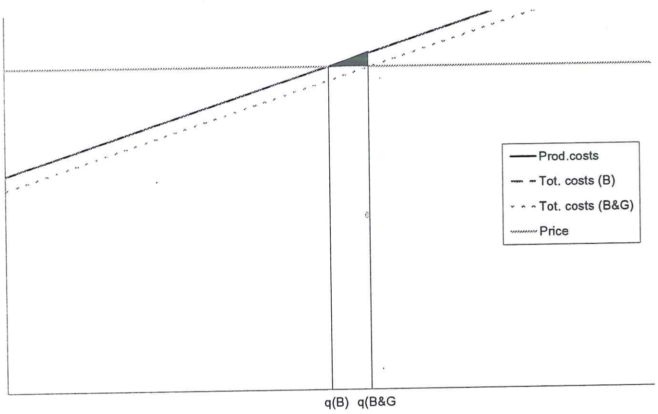


Figure 1c.: *G* production in Black (B) and Black&Green (B&G) scenarios



If the price of electricity falls or rises, we may get additional welfare losses. For instance, if the price falls and consumption increases, the additional cost of producing the extra units will exceed the consumers' willingness to pay for these units.

Within an economy-wide model the excess cost in the electricity market will translate into lower overall income to the consumers (e.g., through lower profits to electricity producers). This will reduce the consumption of all normal goods at given prices. Thus, even if the end-user price of electricity remains unchanged in the partial equilibrium framework discussed above, consumption may fall because of economy-wide income effects.

3. Numerical analysis

3.1 Simulation model and parameterization

In order to illustrate 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 EU electricity market. 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 electricity supply capturing imperfect substitutability between different loads. After accounting for taxes and grid fees the electricity supply together with net imports must satisfy price-responsive electricity demand.

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[7] Obviously, shifting production only from B_2 to B_1 (and not to G) would reduce total production cost, but then the emission constraint would be violated because B_1 has higher emission intensity than B_2.

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).[8] 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.[9]

The model is calibrated to base year data for 2004, as a reference year before the EU electricity sector became subject to CO_2 emission reduction constraints 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 International Energy Agency (IEA 2010). 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).

3.2 Policy scenarios and numerical results

The policy background for our central case scenarios is provided by the EU Climate and Energy Package to fight climate change. According to the Package, the EU is obliged to cut its overall greenhouse gas emissions by 20 % below 1990 levels by 2020 with an overproportional contribution from the power sector as the major emitter. It has also adopted the target of increasing the share of renewables in total energy use to 20 % by 2020 (European Commission 2008b), which translates into substantially higher target shares of renewable energy in electricity production.

Against this policy background we illustrate the implications of overlapping black and green quotas for the EU electricity sector taking a 25 % CO_2 emission reduction vis-à-vis the base year 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

[8] 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 (mathematical program).

[9] The appendix provides 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 available from the authors upon request.

BLACK&GREEN), cf. Table 1. Scenario BMK captures the base year situation of the EU power sector in the absence of black and green quotas.[10]

Table 1: Overview of central case scenarios

Scenarios	Black quota	Green quota
BMK	Not assigned	Not assigned
BLACK	25 % below BMK emission level	Not assigned
BLACK&GREEN	25 % below BMK 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 in the EU endogenously increases from 16 to 18.6 %. Thus, in scenario BLACK&GREEN the share of green power production is imposed to go up from 18.6 to 28.6 %, keeping the emission constraint fixed (the emission constraint is always binding in our policy scenarios).

As sketched in Figure 2, imposition of a green quota on top of the black quota causes substantial additional economic cost. This must be considered as an excess burden if emission reduction is the only policy objective.[11]

Without a green quota, the compliance cost of a 25 % cutback of emissions in the EU electricity system amounts to roughly 7.25 billion Euros. With increasing shares of green power the cost rises up to around 11.85 billion Euros, i.e., compliance cost increase by more than 60 % as 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 28 % 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 11.5 % higher than the BMK price (cf. Figure 3); imposition of an additional green quota leads to increased electricity demand/production as compared to the BLACK scenario.[12] Consistent with reduced end-user prices, total electricity production increases in BLACK&GREEN compared to the BLACK scenario. This is depicted in Figure 4, which also shows that total black production falls and total green production rises.

The price of CO_2 is 41 € per ton of CO_2 in the BLACK scenario, but declines to 16 € per ton when the green quota is also imposed (cf. Figure 5) since the increased share of renewables reduces the pressure

[10] The EU ETS covers not just the electricity sector, but also energy-intensive industries. Moreover, the renewable target applies to the whole economy, and not just the electricity sector. Nevertheless, a majority of emission reductions and increased renewable energy production will most likely take place in the electricity sector, making our simulations results relevant.

[11] 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, enhanced technological progress etc.

[12] 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.

on the emission quota. As a consequence, the green quota does not only increase renewable power generation but benefits the most CO_2-intensive power producers at the expense of non-renewable technologies with low or zero CO_2 intensity (cf. Böhringer and Rosendahl 2010).

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 around 80 % 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 6, which sketches the change in output of the dirtiest technology compared to the BMK scenario. When the green quota is increased by 10 percentage points, output from lignite power plants only decreases by roughly 25 % below the BMK level.

So far, we have quantified the effects of an overlapping green quota for a fixed emission constraint of 25 % below BMK emissions. Figures 7 provides 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). We see 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 2: Percentage change in compliance cost for BLACK&GREEN compared to BLACK

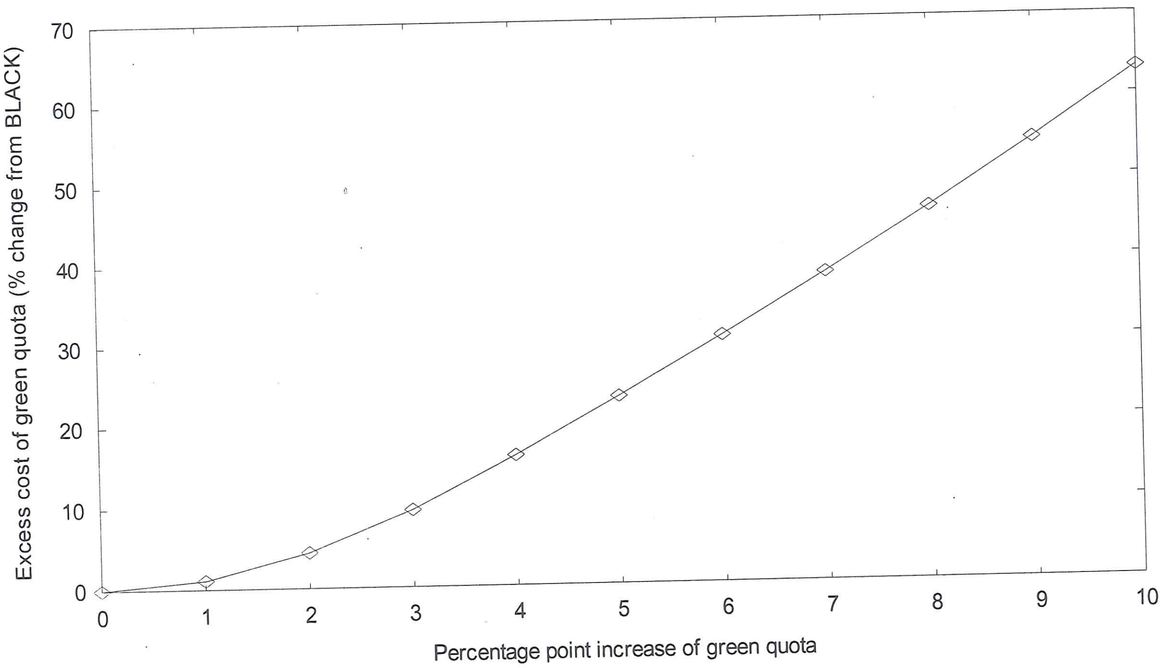


Figure 3: Percentage change in end-user electricity price for BLACK&GREEN compared to BMK

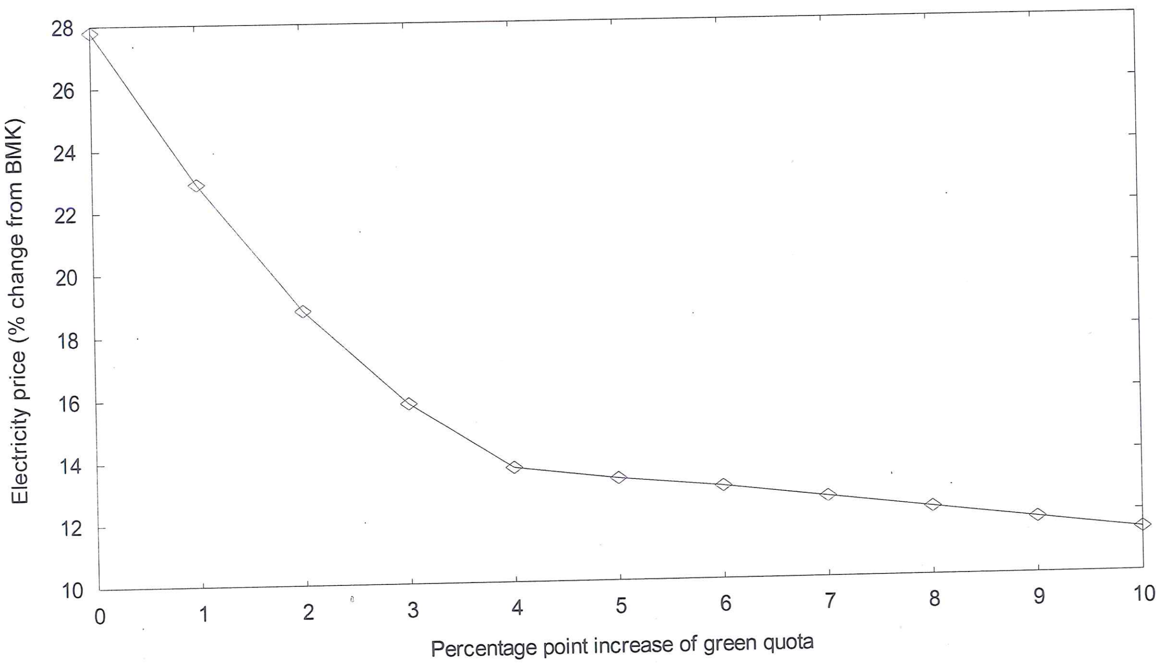


Figure 4: Percentage change in electricity production for BLACK&GREEN compared to BMK

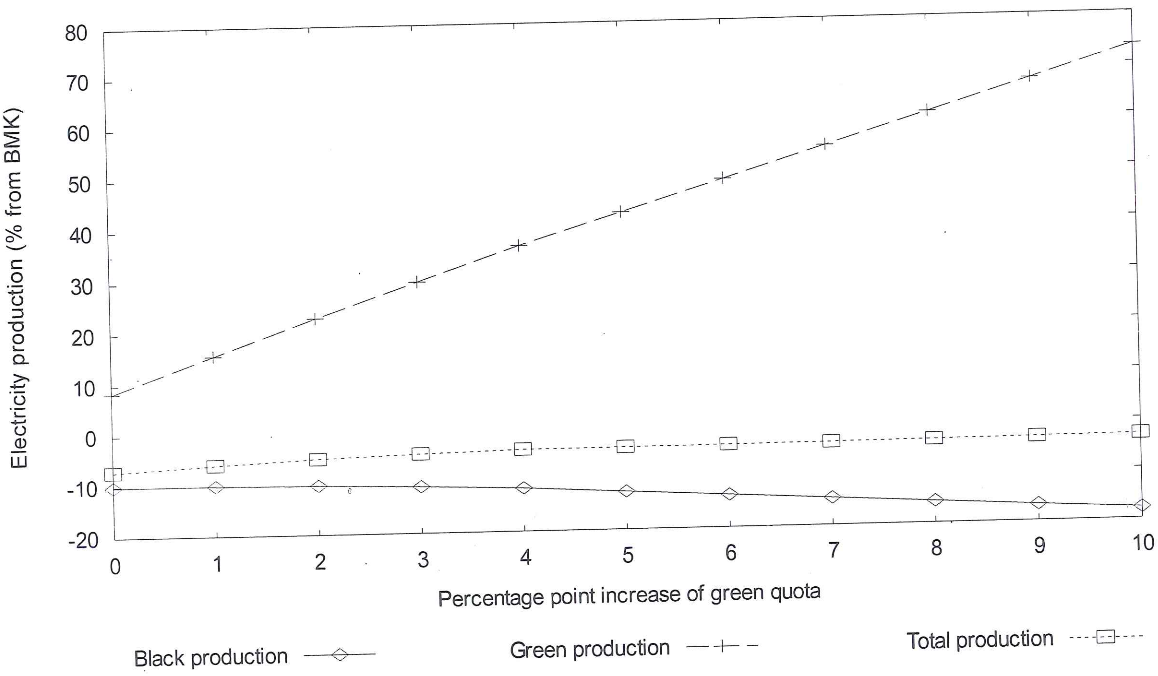


Figure 5: CO_2 price in BLACK&GREEN (Euro per ton of CO_2)

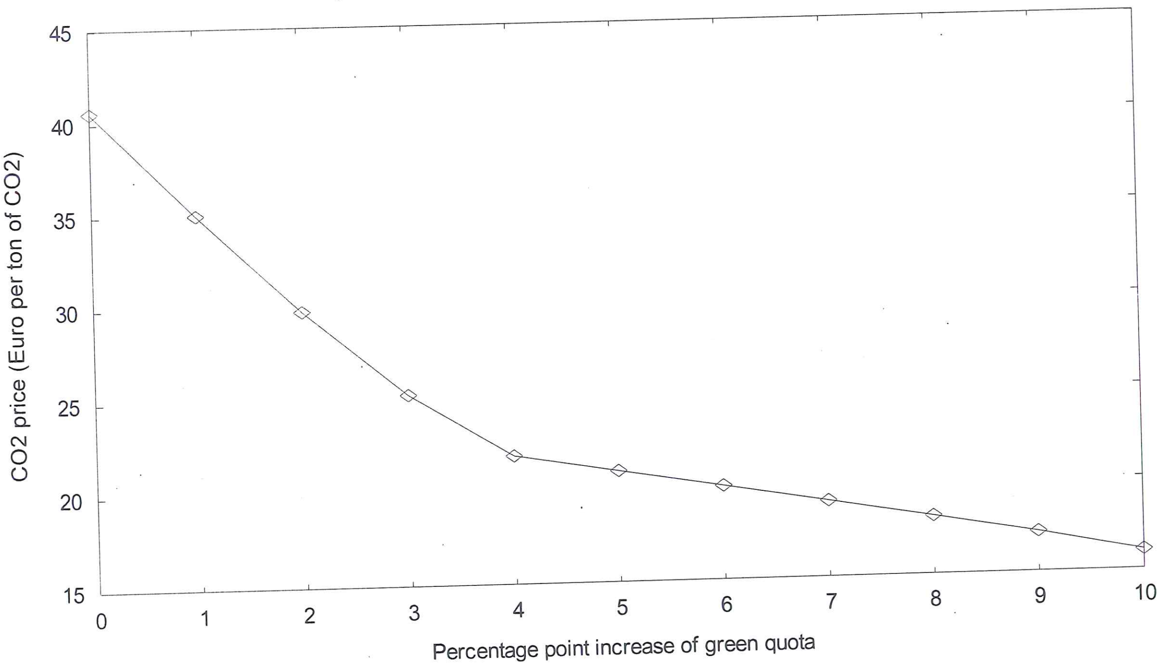


Figure 6: Percentage change in lignite power production for BLACK&GREEN compared to BMK

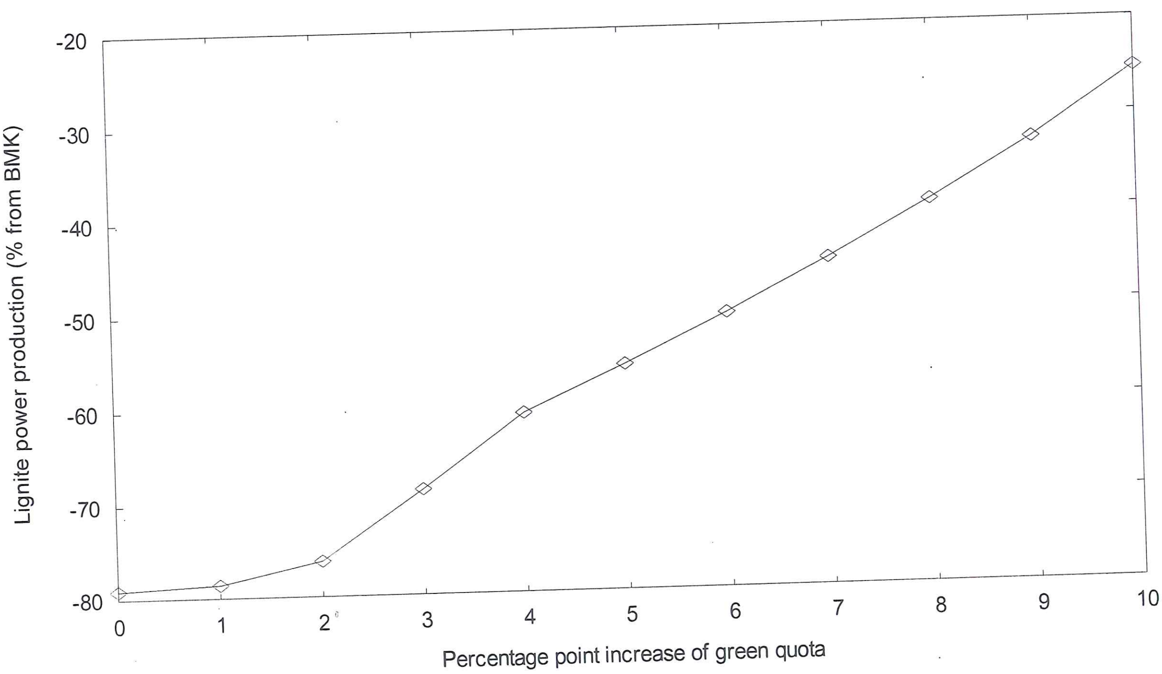
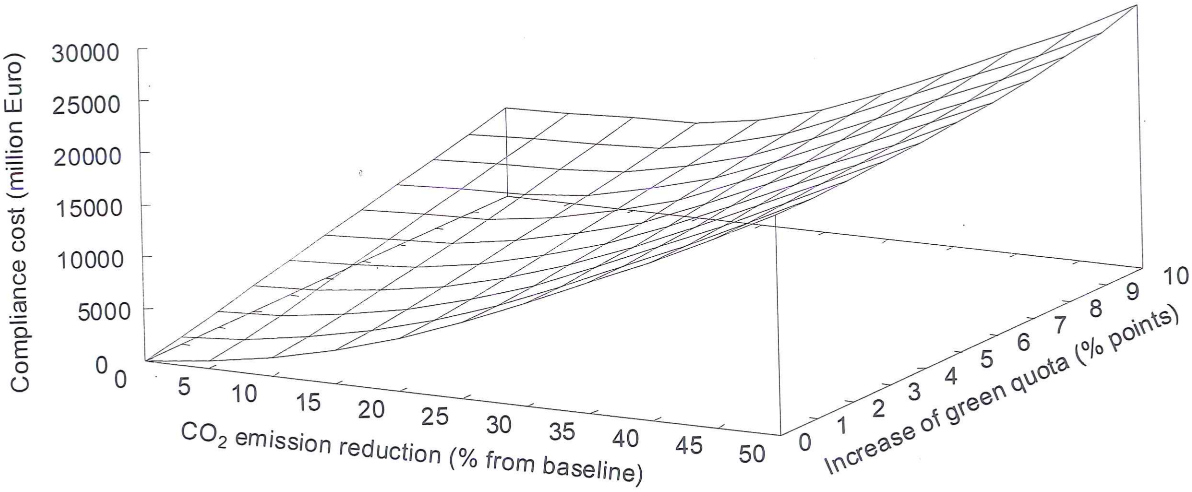


Figure 7: Compliance cost compared to BMK (in million Euros)



4. Conclusions

We have highlighted the pitfall of overlapping regulation in EU climate policy, which prescribes target shares for renewable energies on top of emission quotas. From the sole perspective of climate policy, supplementing an emission cap-and-trade with a green quota is counterproductive. If the emission cap was binding, the green quota would have no effect on emissions (unless they become so stringent that the renewable policy stand-alone causes emissions to fall below the emissions target). At best, the green quota would be redundant if the renewable constraint is already met by the cap-and-trade system. But the more likely result is to raise the overall cost of the emissions cap by inducing excessive abatement from expansion of renewables and too little abatement from other emission mitigation options, i.e., fuel switching among non-renewable energy sources and efficiency improvements.

At second glance, green quotas imposed on top of an emission constraint do not only induce substantial excess cost but have surprising implications on the technology mix. Under a binding emissions cap, a green quota benefits not just renewable producers but also the most CO_2-intensive power producers (in particular lignite), while other low and zero carbon sources (like gas, nuclear and coal with carbon capture and storage) lose out. The explanation for this presumably unintended effect of renewable policies is that the price of CO_2 allowances falls, which is especially beneficial for the most emissions-intensive power plants (cf. Böhringer and Rosendahl 2010).

Our numerical simulations of overlapping regulation for the EU power sector reveal that the additional cost of imposing a green quota on top of a black quota can be quite substantial. That is, 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. One argument for additional green quotas could be that the market penetration of renewable fuels, even under an emission cap-and-trade system, may otherwise be too limited, due to technology spillovers. However, at present there is hardly any empirical evidence on the magnitude of these knowledge spillovers for relatively new technologies like wind and solar, so it is difficult to judge to what extent green quotas are justified as a complementary measure. Moreover, a target for total renewable energy generation is hardly the best way to internalize learning effects for new energy technologies.

Another possible rationale for green quotas is energy security in terms of reduced import dependence for oil and gas (see e.g. Aune et al., 2008). With a cap-and-trade system in place, this effect might be strengthened because additional green quotas will expand both renewable power as well as coal power production, partly at the expense of gas power (the effect of green quotas on oil imports is more modest and indirect, because oil is only marginally used in the power sector). Again, it is difficult to translate energy security in terms of reduced import dependence on fossil fuels into monetary economic benefits that may offset the additional cost of green quotas.

Additional policy targets beyond greenhouse gas emission control call for the use of multiple instruments. However, policy makers must be explicit on the economic rationale of such targets, building upon rigorous cost-benefit analysis, and not just refer to vague catchwords such as increased energy security or strategic technological innovation. Moreover, the relative contribution of renewables should be determined by markets, regulated by a suitable set of policy instruments, and not mandated by policy makers.

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Appendix: Algebraic Summary of Numerical Model

In this appendix we present the algebraic formulation of our numerical electricity market model. Tables A1-3 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 A1: 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 A2: Parameters

$\overline{y}_i$	Base-year electricity output by technology i (TWh)
$\overline{s}_l$	Base-year electricity supply by load l (TWh)
$\overline{s}_i^l$	Base-year electricity load supply by new vintage technology (TWh)
$\overline{z}$	Base-year aggregate domestic electricity supply (TWh)
$\overline{x}$	Base-year electricity exports (TWh)
$\overline{m}$	Base-year electricity imports (TWh)
$\overline{d}$	Base-year final demand of electricity (TWh)
$\overline{p}_i$	Base-year output price for power generation by technology i (Cent/KWh)
$\overline{p}_l$	Base-year load-specific price of electricity (Cent/KWh)
$\overline{p}$	Base-year consumer price of electricity (Cent/KWh)
$\overline{p}_{Int}$	International electricity price (Cent/KWh)
T	Electricity taxes and fees (Cent/KWh) ($\overline{t}$:= base-year taxes and fees)
G	Electricity grid fee (Cent/KWh) ($\overline{g}$:= 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 A3: 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)

A.1 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 $(\perp s_l)$:

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

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

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

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

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

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

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

A.2 Market-clearance conditions

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

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

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

- 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 $(\perp p^{CO2})$:

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

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

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

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