Interactions between measures for the support of electricity from renewable energy sources and CO₂ mitigation

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ABSTRACT

As Europe wants to move towards a secure, sustainable and competitive energy market, it has taken action, amongst other, to support electricity from renewable energy sources (RES-E) and to mitigate CO₂ emissions. This paper first qualitatively discusses price- and quantity-based measures for RES-E deployment as well as CO₂ mitigation. Next, a simulation model is developed to quantitatively discuss the effects of a tradable green certificate system, a premium mechanism, a tradable CO₂ allowance system and a CO₂ tax on both RES-E deployment and CO₂ mitigation. A three-regional model implementation representing the Benelux, France and Germany is used. In a first step of simulations, all measures are implemented separately. In a second step, combinations of both RES-E supporting and CO₂ mitigating measures are simulated and discussed. Significant indirect effects are demonstrated, especially for RES-E supporting measures on the reduction of CO₂ emissions. Interactions between different measures show that the price level of quantity-based measures can be strongly influenced.

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1. Introduction

European legislation is forcing member states towards a secure, sustainable and competitive energy market. On the one hand, electricity from renewable energy sources (RES-E) is expected to contribute strongly to those three pillars of energy policy. However, these technologies are not yet competitive with conventional generation techniques. On the other hand, the deployment of renewables can be seen as only an interim step towards the final objective of reducing CO₂ emissions. As a consequence, simultaneous interest should be paid to measures for the support of electricity from renewable energy sources and CO₂ mitigation.

The importance of RES-E has been stressed from the first moment steps were taken towards the liberalization of the European electricity sector (European Commission, 1996). Member states were allowed to grant an exemption to the non-discriminatory grid access principle for RES-E producers. Additionally, consumers were obliged to purchase a certain percentage of their electricity demand, originating from renewables. Later, an indicative target to produce 21% of the electricity from RES by 2010 was set in the Renewables Directive (European Commission, 2001). Other directives focused on the promotion of biofuels (European Commission, 2003a) and taxation of energy

products (European Commission, 2003b) and two communications emphasized the need to make renewable energy technologies competitive or to bring them to the market (European Commission, 2006, 2007). Recently, the European parliament has gone one step further and sealed the climate action plan. This approval aims to ensure the achievement of the 2020 targets (European Commission, 2008a, b).

The importance of CO₂ mitigation has first been stressed in the 1990s. Many countries joined the international treaty to consider what could be done to reduce global warming and to cope with inevitable temperature increases. This resulted in the United Nations Framework Convention on Climate (UNFCCC) following the Rio Earth Summit on May 9, 1992. This convention has been extended and updated to the Kyoto Protocol on 11 December 1997. The recently signed European climate action plan also enforces a 20% CO₂ emission reduction, which can even be strengthened to 30% in case of an international agreement.

On the one hand, different measures can be suggested to facilitate the introduction of RES-E into the electricity market. Feed-in and quota restrictions based on tradable green certificates (TGC) are installed in different member states (Ragwitz et al., 2007). These measures are often supplemented with fiscal incentives, investment grant or tendering schemes. On the other hand, measures are needed to reduce CO₂ emissions, aiming to limit the global average temperature increase below 2 °C (European Commission, 2007). Quantity-based emission allowances or a price-based CO₂ tax could contribute to reaching the targets imposed.

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Nomenclature

Parameters

C	cap on CO ₂ emissions
K	quota on RES-E
PR	premium for RES-E support
T	tax on CO ₂ emissions
α_i, β_i	coefficients of the demand curve of region i
γ_{ij}, ρ_{ij}	coefficients of the marginal cost curve of region i for technology j
χ_i	coefficient of the marginal pollution curve of region i

Variables

B_i	overall benefit in region i
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C_i	overall cost in region i
D_i	demand in region i
MC_{ij}	marginal cost in region i for technology j
MP_i	marginal pollution in region i for technology j
Q_{ij}	electricity generation in region i with technology j
P_i	price for electricity in region i
P_c	price of CO ₂ allowance
Pe_i	energy price in region i
P_k	price of green certificate

Sets

I	set of indexes of the different regions
J	set of indexes of the different technologies

Research in the literature is mainly theoretical, focusing on the effectiveness and cost-efficiency of different measures. With regard to RES-E deployment, current success stories with great effectiveness of the stable feed-in system are contrasted with least-cost installation and harmonization opportunities that can be expected under tradable green certificates. Besides, the latter is said to have a higher level of market-conformity (Morthorst, 2003a). Further, the interactions between those measures and CO₂ mitigation measures are mainly theoretically studied (Boots, 2003; Jensen and Skytte, 2003; Morthorst, 2001) with a literature overview given in González (2007). Sorrel and Sijm (2003) as well focus theoretically on the coexistence of the carbon trade EU ETS system with several policy instruments, including RES-E measures. As a consequence this paper aims to study the effect of, and interactions between different measures quantitatively (Morthorst, 2003b). Additionally, direct and indirect effects are analyzed. Towards this aim, a three-regional welfare maximizing simulation model is developed, with each node having significantly deviating characteristics.

In the next section, different measures in the electricity market are briefly compared. An overview of both measures with regard to RES-E and CO₂ are first qualitatively given. In the following section, the model, used to investigate the effect of those measures quantitatively, is described. Thereafter, simulation results are presented, based on which, conclusions are drawn in the final section.

2. Different measures for RES-E support and CO₂ mitigation

This section briefly presents the characteristics of different measures that can be taken. Additionally, possible interactions between the direct RES-E support and the CO₂ measures are qualitatively described. It is not the authors' intention to give a thorough overview of all distinguishing features, but some elements are worth mentioning with regard to interpreting the model results.

2.1. Measures for RES-E support

RES-E support is a subsidy that makes renewable energy technologies relatively cheaper and consequently reduces the price gap between this technology and the conventional power generating technologies. An overview of the different measures implied in the EU-15 is shown in Table 1 (Krohn et al., 2009). The subsidy to push RES-E into the market is offered as an additional

price for the green label of electricity generated by RES-E technologies. This remuneration corresponds to a shift from long run marginal cost (LRMC) curve for renewables 1 (LRMC res1) to a lower level LRMC res2 in Fig. 1. RES-E technologies end up to be more competitive and get introduced into the electricity market. As this additional remuneration is offered outside of the wholesale electricity market, the market energy price is not expected to be strongly influenced in contrast to the retail price, faced by the final consumers (Jensen and Skytte, 2002). Through the deployment of RES-E technologies, polluting conventional power generating technologies are replaced, indirectly inducing a decrease in CO₂ emissions. The effectiveness of this indirect influence is however uncertain (Marchenko, 2008).

2.1.1. Quantity-based

Policy makers can decide on the level of renewable energy that has to be deployed into the market. When this level is expressed as a percentage of final consumption, it is referred to as a quantity-based measure. The TGC system is the quantity-based measure offering direct RES-E support. Certificates, which can be seen as financial instruments, are traded on an artificial market to facilitate reaching previously defined quota obligations or targets (Morthorst, 2003a). Market-conformity is introduced by establishing a target for a share of electricity originating from renewables, with or without an intermediate trajectory. As the target is expressed as a percentage of renewable energy for total demand, policy makers also have the incentive to reduce demand and consequently improve energy efficiency. It is often mentioned

Table 1

Overview of RES-E supporting measures in EU-15.

Country	RES-E supporting measure
Austria	Feed-in tariffs
Belgium	Tradable green certificates with guaranteed minimum prices
Denmark	Tendering for offshore/premium for onshore/feed-in for other
Finland	Tax and discretionary investment subsidies
France	Feed-in tariffs/tendering for large scale projects
Germany	Feed-in tariffs
Greece	Feed-in tariffs/investment incentives
Ireland	Feed-in tariffs
Italy	Tradable green certificates/feed-in tariffs for PV
Luxembourg	Feed-in tariffs
Netherlands	Premiums (put at zero from August 2006)/investment incentives
Portugal	Feed-in tariffs/investment incentives
Spain	Feed-in tariffs
Sweden	Tradable green certificates
UK	Tradable green certificates

Fig. 1. RES-E and CO₂ measures and interactions between them.

that significant price uncertainty is introduced through this supporting measure. Two volatile remunerations can be expected for the electricity generated and the green label, respectively.

2.1.2. Price-based

Price uncertainty can be reduced when policy makers decide to offer a fixed price for the green label. This makes that only one element, i.e., the electricity price, is determined on the unpredictable market. This is called the premium, referring to the fixed bonus for the green label.

Risks involved with electricity price fluctuations can even be fully eliminated. In this final case one fixed price is offered for the electricity generated using renewable energy technologies. This feed-in system creates significant stability in the system with the inherent lack of market-conformity. No additional market is created for the remuneration of the green label, nor do RES-E power generators bid into the energy market.

The cost-efficiency and effectiveness of the TGC and the feed-in system is strongly debated and mostly driven by chauvinistic preferences. The price-based feed-in system is often supported based on its effectiveness (Butler and Neuhoﬀ, 2004; Menanteau et al., 2003). This can be seen as a direct result of increased stability and reduced investment risks. It also easily facilitates encouraging technological diversity and the development of a diversified RES-E portfolio. The fixed price level, however, has the disadvantage that the amount of RES-E that is finally generated remains uncertain. Is a member state going to overshoot the target, or will they fall short?

2.2. Measures for CO₂ mitigation

CO₂ emissions can be reduced by several means. For each case, external social costs, due to the emission of CO₂, are priced and make polluting thermal technologies more expensive. Consequently, RES-E technologies become relatively less expensive. As the initial cost disadvantage is reduced, renewable energy technologies become more competitive. Corresponding to RES-E measures, the gap between RES-E technologies and conventional power generating technologies is reduced. However, in this case, the conventional technologies are made more expensive, shifting from LRMC conv1 to conv2 in Fig. 1. Even though no additional remuneration is offered to electricity generators using RES-E

technologies, the RES-E share of final demand can be expected to increase.

2.2.1. Quantity-based

Whereas member states are highly inconclusive about the best instrument to introduce RES-E directly into the market, one single European wide approach for CO₂ mitigation exists. Following the Kyoto protocol, Europe has decided to install the European Union Emission Trading Scheme (EU ETS). This emission allowance trading (quantity-based measure) was the way forward to reduce emission cost effectively. For every tonne of CO₂ emission, an allowance has to be surrendered. Similar to with the quantity-based RES-E measure, an artificial market is created to trade emission allowances, which can be seen as financial products.

2.2.2. Price-based

The price-based alternative for CO₂ emission reduction is a CO₂ tax. A fixed price level could have been chosen for a certain amount of CO₂ emitted (e.g. one tonne), offering a fixed opportunity cost for investments in emission reductions. Again, price-based measures do not offer an indication of the percentage of emission reduction that should be reached.

2.3. Interactions between supporting measures

As explained above, both measures reduce the cost gap between renewable and conventional generating technologies. Whereas one could have a relatively clear idea of the impact of each system separately on the installation of renewables and the reduction of CO₂ emissions (De Miera et al., 2008), this might not be the case if both are simultaneously put in place.

If one price-based and one quantity-based measure are installed, the fixed price level of one measure could influence the market price of the quantity-based measure. If two quantity-based measures are installed, it is not clear whether one or both quota restrictions will be binding (Unger and Ahlgren, 2005).

3. Modeling of measures

This section describes the model that is developed to gain insight into the impact of different measures to support the

deployment of RES-E and to mitigate CO₂ emissions. These measures have been briefly discussed in the previous section. Accordingly, this model will be used to study the direct effects of, and interactions between, the CO₂ and RES-E measures.

3.1. Model description

The model used in this paper is a welfare maximization model of different interconnected regions. Overall welfare is defined as the sum of consumer and producer surplus, calculated by withdrawing total costs from the total benefits involved with the power system

$$\text{Max} \sum_{i \in I} B_i - C_i, \quad (1)$$

in which index i represents a certain region, B_i is the overall benefit in region i and C_i is the overall cost in region i . The benefit B is determined by the surface below the demand curve, and is therefore defined as

$$B_i = \int P_i dD_i, \quad (2)$$

in which P_i is the price for electricity in region i and D_i is the electricity demand in region i . Each region i has a consumer group characterized by a demand curve

$$P_i = \beta_i - \alpha_i D_i, \quad (3)$$

in which α_i and β_i are coefficients determining the linear demand curve of region i . Demand in each node can be met by two types of power generation j , being conventional (*conv*) and renewable power (*res*)

$$J = \{\text{conv}, \text{res}\}. \quad (4)$$

Each region is characterized by a different long run marginal generation cost for these two types of technology j

$$MC_{ij} = \gamma_{ij} + \rho_{ij} Q_{ij}, \quad (5)$$

in which γ_{ij} and ρ_{ij} are the coefficients of the linear marginal cost curve of region i for technology j , MC_{ij} is the marginal cost in region i for technology j and Q_{ij} is the electricity generation in region i with technology j .

Both investment and variable costs are taken into account, for conventional as well as renewable power generation.

From these marginal costs, the total costs C_i can be calculated as a summation of the integrals of the marginal costs of the different technologies

$$C_i = \sum_{j \in J} \int MC_{ij} dQ_{ij}. \quad (6)$$

Conventional power generation involves the emission of CO₂ with marginal pollution defined as

$$MP_i = \chi_i Q_{i,\text{conv}}, \quad (7)$$

in which χ_i is the coefficient determining the marginal pollution curve of region i and MP_i is the actual marginal pollution in region i for technology j .

Given the regional implementation, transmission of electricity is possible between regions, restricted by taking limited interconnector capacity into account. The transmission lines are considered lossless and having equal impedance, with flows determined by Kirchhoff's laws (DC load flow approximation). The overall clearing condition states that overall demand must equal total supply

$$\sum_{i \in I} D_i = \sum_{i \in I} \sum_{j \in J} Q_{ij}. \quad (8)$$

The model as presented so far is the reference model, with support measures neither for RES-E deployment nor for CO₂ mitigation implemented.

Available measures contributing to reaching the targets set by the European energy policy can now be introduced to this model. As described in the previous section, a distinction has to be made between price-based or quantity-based measures, focusing on RES-E deployment or CO₂ emission reduction. Price-based measures offer an additional fixed financial support. In case of RES-E support, a premium reduces the absolute costs of the RES-E technology and makes renewables as such relatively more competitive. Eq. (6) now becomes

$$C_i = \sum_{j \in J} \int MC_{ij} dQ_{ij} - PR Q_{i,\text{res}}, \quad (9)$$

in which PR is the premium for RES-E support.

In case of a price-based CO₂ mitigation measure, a CO₂ tax increases the absolute costs of conventional power generation and equivalently makes renewables as such relatively more competitive

$$C_i = \sum_{j \in J} \int MC_{ij} dQ_{ij} + T \int MP_i dQ_{i,\text{conv}}, \quad (10)$$

in which T is the tax on CO₂ emissions.

When calculating welfare in these two cases, the total amount of premium and CO₂ tax, needs to be withdrawn from or added to the level of total welfare, respectively, after the maximization.

Quantity-based measures on the other hand add a restriction to the model to enforce a certain percentage K of renewables installed or a certain cap C on CO₂ emissions. The former is presented by Eq. (11) with the dual variable of this constraint being the certificate price P_k

$$\sum_{i \in I} Q_{i,\text{res}} \geq K \sum_{i \in I} D_i \quad (11)$$

The latter is presented by (12), with the dual now being equal to the allowance price P_c

$$\sum_{i \in I} \int MP_i dQ_{i,\text{conv}} \leq C. \quad (12)$$

In order to analyze the interactions between the CO₂ and RES-E measures, both can be implemented simultaneously.

4. Model implementation and simulation

4.1. Model implementation

In this analysis, regions with strongly differing characteristics are used. This allows for evaluation of the impact and interactions of measures in different regions. A three-regional model is employed representing France, Germany and the Benelux (i.e., Belgium, the Netherlands and Luxembourg). With regard to conventional power generation, based on Eurelectric data (Eurelectric, 2008), France is the region dominated by nuclear power whereas the shares of gas and coal/lignite are significant in the Benelux and Germany, respectively.

Differences do also exist between the level of RES-E potential (European Commission, 2004). Within the Benelux only a noticeable offshore wind power potential exists, especially thanks to the Netherlands. Potentials in Germany and France are comparable, apart from the much larger hydro potential in France.

Initial demand levels are also based on Eurelectric data and an inelastic -0.1 price elasticity of demand is considered, meaning that a price increase of 10% only results in a demand decrease of 1%.

Table 2
Input data for the model.

		Benelux	Germany	France
Demand coefficients	β_i	4.20E+02	4.14E+02	3.83E+02
	α_i	−1.60E−02	−5.85E−03	−6.32E−03
Marginal cost coefficients, conventional	$\gamma_{i,conv}$	2.76E+01	2.72E+01	2.33E+01
	$\rho_{i,conv}$	4.44E−04	1.62E−04	2.09E−04
Marginal cost coefficients, renewable	$\gamma_{i,res}$	4.58E+01	4.93E+01	4.88E+01
	$\rho_{i,res}$	1.50E−02	2.77E−03	2.57E−03
Marginal pollution coefficients	χ_i	1.77E−05	9.22E−06	1.14E−06

Fig. 2. Representation of model structure.

Marginal CO₂ pollution takes the current conventional generation portfolios into account for each region. The data in Table 2 summarize the input used for the described model.

A triangular network is considered, with all three lines having equal reactances and a capacity of 3000 MW. A schematic overview of the implementation of the model is presented in Fig. 2.

4.2. Simulation description

The three-regional model is deployed in several simulations. The first part of the simulations concerns the RES-E support measures. In a first step, the effect of a quota on renewables for the three regions together is investigated. This overall quota has been varied from zero up to 60%. In a second step, the effect of a premium has been investigated, ranging from zero to 100 euro/MWh.

The second part of the simulations concerns the CO₂ mitigation measures. Again, both a limitation on overall emissions (zero up to 60%) as well as a price on CO₂ (zero up to 100 euro/t) are investigated.

The third and final part of the simulations involves combinations of both a RES-E support and a CO₂ mitigation measures. A quota on RES-E is at first instance combined with a price on CO₂ (tax), and second, with a cap on CO₂ emissions. The combinations and interactions of these measures are extensively discussed. The main focus of all simulations will be on resulting RES-E deployment and CO₂ emission reduction.

The input data from Table 2 take into account the dominance of different conventional technologies and the different levels of RES-E potential for the three regions. The supporting measures are implemented over the three regions, which corresponds to a

harmonized system. Note that, investigating the impact of harmonizing a supporting measure on welfare is not the scope of this paper.

5. Results

The results of the different model simulations as described above are presented in this section. Furthermore, a reflection upon the simulation results is also presented.

5.1. Measures for RES-E support

The impact of the quantity-based certificate system and the price-based premium system are consecutively discussed.

5.1.1. Tradable green certificates

Imposing targets for a certain percentage of RES-E is facilitated by certificates, having a price equal to the dual price of restriction (11). A target of 0–60% of total electricity demand originating from renewables is implemented in the model. This target can be reached through two approaches: demand can be reduced, e.g., as a result of energy efficiency, or the absolute level of RES-E can be increased. Lower targets are mainly reached by installation of RES-E, while for higher targets it becomes more beneficial to reduce consumers' demand, rather than to opt for more renewables facing significantly increasing marginal costs. Based on the different potentials for RES-E, France reaches the highest RES-E share and the Benelux the lowest (Fig. 3). This is an illustration of the least-cost installation principle when a harmonized support system is in place. Fig. 3 also presents the overall emission of CO₂ across the three regions. The effect of the RES-E measure on CO₂ is impressive, as a significant decrease is presented.

Imposed targets also have an impact on the energy (wholesale) and retail price (Fig. 4). The energy price P_e is in this case equal to the marginal cost of conventional power generation. This energy price is reduced, as conventional power generation is replaced by renewables. Therefore, the marginal conventional technology is less expensive. The retail price faced by final consumers, however, increases and can be calculated as

$$P_i = P_{e_i} + K P_k = MC_{i,conv} + K P_k. \quad (13)$$

5.1.2. Premium

This system is a direct subsidy resulting in a reduction of the initial cost disadvantage. It is modeled in such a way that consumers do not cover the incurred cost of this subsidy.¹ The

¹ If the cost incurred by this premium would be added to the price for electricity paid by the customers, the model would not implement RES-E technologies at all, as it is optimized by an overall welfare maximization. In reality, this cost would be borne by the customer (by general taxes). Therefore, the

Fig. 3. (a) RES-E shares in different regions and (b) overall CO₂ emissions, with a TGC system.

Fig. 4. Price levels with TGC system. Note that the legend presented in panel (c) also applies for panel (a).

retail price is therefore equal to the energy price. Nevertheless, the total amount of premium paid is withdrawn from the social welfare. As a result of the fact that consumers do not face the cost of the feed-in subsidy, the level of demand is not reduced. A minimum feed-in level between 10 and 15 €/MWh is needed to get the first amount of renewables installed. This is similar to the

certificate price of about 14 €/MWh (Fig. 4) to get 1% of RES-E into the market (Fig. 5). The same relative distribution over the three regions can be seen as with the certificate system.

RES-E supporting measures are very effective with regard to the reduction of CO₂ emissions. The larger emission reduction is found for the certificate system. The lacking incentive for energy efficiency with the premium, however, makes it harder to reduce emissions.

5.2. Measures for CO₂ mitigation

CO₂ emissions can be reduced by decreasing electricity generation from polluting technologies. Therefore, one can switch to renewables, reduce demand or increase the share of nuclear power generation. Generation can be shifted to a region with different characteristics. However, due to limited interconnector capacity, the opportunities to replace power generation originating from coal (Germany) or gas (Benelux) are restricted.

Note that if unlimited interconnector capacity would be modeled, France would increase the nuclear power generation significantly and export major amounts of power to the other regions. Since nuclear power is less expensive than installing renewables, RES-E deployment would be strongly delayed. Consequently, it can be stated that in case of unlimited interconnector capacity, the indirect support of renewables is not effective if nuclear power generation is an option.

5.2.1. Emission allowance trading

A target is imposed for a certain percentage of CO₂ emission reduction, by means of emission trading. Allowances have a price equal to the dual price of restriction (12). The target has an impact on the energy (wholesale) and retail price. In this case, the retail and the energy price are the same, but the energy price is no longer equal to the marginal conventional generation cost. The level of pollution of the marginal technology and the allowance price for CO₂ emissions have to be taken into account:

$$P_i = Pe_i = MC_{i,conv} + MP_i P_c. \quad (14)$$

Fig. 6 shows that France is strongly protected against an increase in the imposed quota for CO₂ emission reduction. No renewables need to be installed in France and a stable level of conventional power generation is maintained. Due to the least-cost emission reduction principle when a harmonized system is in place, the Benelux and especially Germany install significant amounts of renewables (Fig. 7). The level of conventional power generation is strongly reduced in these two regions, which can be deducted from the significant decrease in the thermal prices.

(footnote continued)

assumption of decoupling the cost of this premium from the electricity price is justified.

Fig. 5. (a) RES-E shares in different regions and (b) overall CO₂ emissions for different levels of premium.

Fig. 6. Price levels with a CO₂ emission allowance. Note that the legend presented in panel (c) also applies for panel (a).

Therefore both a demand reduction and a RES-E deployment took place.

5.2.2. CO₂ tax

Comparable results are found with the CO₂ tax. Again, France does not really experience a strong impact of this measure with almost unaffected demand and no renewables deployment. While a convex renewables share can be seen in Fig. 7 for Germany and the Benelux, concave curves can be seen in Fig. 8. This can be

explained as follows. In case of the quantity-based allowance mechanism, each additional CO₂ emission reduction is more expensive, resulting in a more than linear renewables deployment. In case of a CO₂ tax, an additional tax increase results in a decreasing slope of renewables deployment due to increasing LPMC for renewables.

Finally, there exists a difference in how the amount of CO₂ emissions is reduced. In case of the allowance mechanism, a linear emission reduction is found, conform the decrease of the cap. On the other hand, the total level of emissions is convex decreasing in case of an increasing CO₂ tax. This is the consequence of the low hanging fruit concept, which states that the first reductions in emissions are more easily achievable compared to those following.

5.3. Interactions between supporting measures

With two measures simultaneously implemented, it is not always clear in advance whether a quota restriction will be binding. If a restriction is not binding, the dual price is zero, which results in a zero certificate or allowance price. First, only one quantity-based measure, TGCs, is studied together with a CO₂ tax which always has an impact. Second, two quantity-based measures are studied. The impact on the installation of RES-E and the reduction of CO₂ remain the main interest.

5.3.1. TGC and CO₂ tax

Different combinations of RES-E quota and CO₂ tax levels are studied. Fig. 9 shows that the renewables quota is not binding for a triangular group of combinations. With a higher CO₂ tax, a higher renewables quota needs to be implemented to become binding. This is logical result, as this CO₂ tax already causes a certain amount of RES-E penetration into the market.

Consequently, it can be seen in Fig. 10 that for this triangle of non-binding renewables quota, the RES-E share is only driven by the CO₂ tax, while for other combinations both instruments determine the total RES-E share. Additionally, Fig. 9 shows that the TGC price is lower when a higher CO₂ tax is in place. This results out of the fact that a higher CO₂ tax already reduces the cost gap between conventional and renewable power generating technologies to a higher extent. A smaller additional support, by means of the certificate price, is therefore required for an even higher renewables share (Fig. 10).

The non-binding triangle can also be recognized in Fig. 10(b). Combinations can be seen where for a certain CO₂ tax, the quota levels do not have an impact on the total emissions. It can also be seen that the influence of a CO₂ tax fades as quota levels on RES-E increase.

Fig. 7. (a) RES-E shares in different regions and (b) overall CO₂ emissions with a CO₂ emission trading scheme.

Fig. 8. (a) RES-E shares in different regions and (b) overall CO₂ emissions with a CO₂ tax.

Fig. 9. Certificate price for combinations of TGC and a CO₂ tax.

5.3.2. TGC and emission allowances

Two quantity-based measures can also simultaneously be installed with quota restrictions on the amount of emission reduction and the share of renewables. It can be seen on Fig. 11 that three planes exist for both the certificate and the allowance price. These planes represent the quota combinations for which only one or both restrictions are binding. From Fig. 11(a) it can be seen that for a relatively high quota on renewables, the certificate price is only dependent on this quota, while being independent from the restriction on CO₂ emissions. On the other hand, at relatively low RES-E quota and high CO₂ emission restrictions, the

RES-E quota restriction becomes a non-binding constraint, and hence, yields a zero certificate price. Fig. 11(b) presents the allowance price. A large plane with a zero allowance price can be seen, which corresponds to the plane in panel (a) that is independent from the CO₂ emission restriction. Only a narrow plane exists at relatively high CO₂ restrictions and low RES-E quota, which has a significant allowance price, and a non-binding RES-E constraint. The slanting planes in both panels (a) and (b) correspond to the situation where both the RES-E quota and the CO₂ emission restriction are binding constraints.

Fig. 12(a) presents the renewables share in the Benelux. Comparing Fig. 12 with Fig. 10 clearly illustrates that a tax always has its impact. Even at very high quota for renewables, it still influences the share of renewables (and hence the certificate price). When, on the other hand, two quantity-based measures are simultaneously implemented with one being highly stringent, the other becomes non-binding and loses its impact. This creates significant uncertainty when certain investments are fully based on the remuneration through one measure.²

5.4. Reflection upon simulation results

A first remark concerns the realism of the presented simulations. No model is perfect and inherent to any modeling exercise, certain assumptions and simplifications are made. In the

² Note that there are other sectors subject to EU ETS, next to the power sector. These are, however, not covered in this model. As sort of a residual quota on CO₂ emissions is modeled for the power sector solely, the price of allowances can drop to zero at sufficiently high levels of quota on RES-E. In reality, there will be interaction with the other ETS sectors, and the allowance price will not drop to zero that easily.

Fig. 10. (a) RES-E share in region 1 and (b) overall CO₂ emissions for combinations of TGC and a CO₂ tax. Note that both the X and Y axes have a reversed direction in panel (b).

Fig. 11. (a) Certificate price and (b) allowance price for combinations of TGC and CO₂ allowances. Note that the X-axis has a reversed direction in panel (b).

Fig. 12. (a) RES-E share in region 1 and (b) overall CO₂ emissions for combinations of TGC and CO₂ allowances. Note that both the X and Y axes have a reversed direction in panel (b).

employed simulations, two types of technologies are incorporated for each region, being conventional and renewable electricity generation. Both of these technologies are characterized by a linear marginal cost curve, while the conventional technologies additionally have a linear marginal CO₂ emission rate. These cost and emission functions have been determined for the modeled regions as adequate as possible. Nevertheless, given the assumptions, the focus really should be on qualitative trends, rather than on numerical results, which should be interpreted with care. Further extending the model by including more regions, more types of technologies and using more complex functions to describe these technologies might be an option for future work.

Note that in this work, only the power sector is considered. Both RES and CO₂ targets and corresponding measures could be implemented over several sectors (e.g., heating and cooling, transport). Including such different sectors in the model reveals a second direction for further extending the model. However, the availability and adequacy of good data required for this modeling extension might pose a limitation.

Trends in the outcome of the model are comparable with conclusions made in Jensen and Skytte (2002) even though only one region is considered. The three-regional model in Morthorst (2003b) on the other hand is difficult to compare with, as the interactions between the different regions based on RES-E

potentials and different generation portfolios are not taken into account. Furthermore, the impact on the price of the quantity-based measure and whether targets are binding is not discussed. The conclusions of the equilibrium model developed by Abrell and Weigt (2008) to investigate the interactions between different measures in Germany are however strongly comparable.

A final remark relates to the implications of the obtained simulation results for specific policies. It has been demonstrated that measures for RES-E support have an influence on CO₂ emissions and vice versa (especially the effect of RES-E supporting measures on CO₂ mitigation is noticeable). If only one such measure (either RES-E support or CO₂ mitigation) is implemented, this measure is an actual binding constraint and results correspond to what can be expected. If, however, a combination of different measures is implemented, the outcome might be more surprising. E.g., if a quantity-based measure becomes non-binding, the price of the corresponding TGC or CO₂ allowance becomes zero. Such a situation might not be desirable for a stable investment climate.

6. Conclusion

Mostly, research has been focusing on the theoretical comparison of characteristics of different supporting measures for renewable energy and CO₂ mitigation in the European electricity market. This paper tries to study these characteristics quantitatively by the use of a welfare maximization simulation model.

The impact of price-based and quantity-based measures concerning RES-E support and CO₂ mitigation is investigated, in combination with the interactions between these measures. It can be concluded that quantity-based measures offer an incentive to reduce demand and stimulate energy efficiency. The CO₂ tax system also reduces demand as consumers directly face the impact of the increased price level, which is not the case for a premium.

In general, a single measure (either RES-E support or CO₂ mitigation) induces both the installation of renewables and the reduction of CO₂ emissions. Although a measure should be used in essence to contribute directly to meeting its targets, it also has an indirect impact. In this regard, an increased target for a RES-E share is more effective in reducing CO₂ compared to using a CO₂ approach for increasing the RES-E share. When a CO₂ measure is implemented, it is clear that nuclear becomes a very interesting option. Consequently, countries with a high nuclear power share face little problem and experience almost no renewables deployment.

Finally, it can be concluded that different support measures influence each other. Price-based measures always have an impact, in contrast to quantity-based measures. In the latter, the outcome can significantly be influenced as the price for certificates or allowances can become zero with non-binding restrictions. This creates significant uncertainty when investments in renewables or in emission reductions are based on only one remuneration measure.

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