Cap-and-Trade Design and Intrinsic Boundaries to RES Conversion of Energy Systems

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Abstract

The analysis of cap-and-trade systems as a policy tool to control the enivronmental impact of polluting productions has been long investigated in the economic and financial literature. There is a general consensus among the scientific community that they represent a cost efficient method for a society to drive companies to adopt environment friendly technologies. However the major world application of this regulatory policy, namely the EU ETS for the control of the greenhouse gases, has raised several new criticisms both from the political and the scientific sides. The lack of a substantial renewal of the old polluting technolgies (i.e. coal) in favor of most green ones (e.g. renewable energy sources or natural gas) in the power sector is a major critique. The electricity sector contributes today to more than 60% of the total emissions in the EU. Regulatory imperfections, like the grandfathering of the emission certificates, as well as the uncertainty of the regulatory framework have often been pointed as responsible for that problem.

In this paper we develop a streamlined model which integrates the economy of the power sector and the market of emission certificates. The relevance of this integration consists of linking the output price (of electricity) to the cost of the emission certificates. This modifies significantly the classical cost-efficiency analysis of cap-and-trade systems, where the output price is taken as a fixed parameter. Power markets, on the contrary, are characterized by an almost totally unelastic demand and a uniform price auction system. Besides, the relatively high level of concentration of the EU power sector justifies the hypothesis that the decision about the renewal of technological plants is not fully competitive in this sector. Under these settings our model shows that the economic incentives introduced by cap-and-trade systems are contrary, or useless at best, to enhance investments in green technolgies.

1 Introduction

Cap-and-trade systems have been introduced in the EU and the US as a major instrument to convert the production systems towards environment friendly technologies. In the case of the EU

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the Emissions Trading System (EU ETS) sets a maximum boundary on the quantity of greenhouse gases (GHGs, mainly CO2) to be emitted in the atmosphere. A given number of certificates (Emission Unit Allowances, or EUAs) are issued by the regulatory authority and are distributed among the producers, and each unit represents the right to emit 1 tonne of CO2. During a market phase producers can not emit a quantity of CO2 exceeding that represented by their certificates. They can however go to the market and buy more EUAs from producers in excess of those certificates (or from other institutional market traders). If no allowances are available on the market, a penalty is due for every tonne of CO2 emitted without a corresponding allowance.

The economic theory of cap-and-trade systems has developed since the original contribution of Montgomery (1972). Since this work, the literature has recognized that, from a theoretical point of view, such systems are cost-efficient, in the sense of minimizing the total cost required to the society to switch production systems towards more environment friendly technologies.

Nevertheless several criticisms have raised since the EU ETS has been introduced, due to several regulatory aspects (e.g., grandfathering of initial issues, banking and borrowing mechanisms), or to the effects of the global economic crisis on the EU ETS (e.g., the decline in the economic growth of Western countries that is driving the EUA prices to very low levels). Among the others, a critical aspect, often cited in the public discussion, is that the fuel-switch in the production plants (especially in the electricity sector, which is the major CO2 emitter) originated by the EU ETS is not taking place at the expected rate (see the case of Germany, where the electricity generated through coal plants is expected to raise by 33% between 2013 and 2015, McCown, 2013). The major reason which has been identified as a responsible of this problem is that the EUA prices have been too low during the first two market phases, which took place in 2005-2007 and 2008-2012, respectively. In turn, the weakness of the EUA prices has been seen as the result of several other factors, such as the economic crisis enduring since more than 8 years now, and the excess of certificates distributed at the beginning of the first two market phases. The recent “Commission Regulation (EU) No 176/2014”, adopted by the European Commission and restricting the number of certificates to be issued in the first part of phase III (2013-2020), reflects the urgent need to contrast the problem of very low prices of emission certificates.

While the low price is indeed a strong argument, easily and frequently cited by most analysts, we argue in this paper that the current designs of the electricity market and the emission certificates market contain also an intrinsic boundary (and, as such, not immediately observable), binding the power sector from a thorough renewal of its technological base.

The model we advance focuses on the aggregate decision of the individual producers and points out that they will find an economic boundary preventing them to pursue fuel-switching any further. Our major conclusion is that the optimization of the initial number of certificates (which will circulate during a market phase) can not be a sufficient tool to push the power sector to renew its conventional technology base, unless complementary/supplementary policies are introduced to correct the effect of the intrinsic boundary.

2 Preliminary settings

We consider an economy of power producers in a one period setting, where time goes from 0 to $T > 0$. Each producer is endowed with plants of two possible technologies, renewable energy sources (RES) and conventional energy sources, with capacities Q_{nc} and Q_c, respectively. The demand of electricity for the period $[0, T]$ is a random variable D with given distribution.

We assume that demand is inelastic. Actually, for the purposes of this discussion, assuming that the demand of electricity depends slightly on prices would not change the conclusions of this work, so assuming total independence of the demand from prices, just simplifies the analytical treatment of the model.

We let $c_{v,nc}$ and $c_{v,c}$ represent the direct costs required to generate 1 MWh, respectively, for the non-conventional and the conventional plants. Conventional plants are also required to cover their CO2 emissions by means of emission allowances. If a conventional plant emits m tonnes of CO2 to generate 1 MWh, the (unit) environment cost is $c_a = mp_a$, where p_a is the (time 0) price of an emission certificate.

At time 0 the authority issues a C emission certificates. Given the transformation parameter m cited above, this corresponds to a conventional production of $H = C/m$ MWh which can be 'covered' with the issued certificates.

In this paper we consider an expansion capacity problem. Expansion can be negative, i.e. we allow for a reduction of production capacity. At time 0 producers can decide to expand their production capacity. We suppose that these expansions are immediately put in place. Let the quantities Q_{nc}^* and Q_c^* represent the expansions of production capacity for the non-conventional and the conventional plants, respectively.

In short, the story of this paper is as follows. At time 0 the authority issues C emission certificates at a cost equal to p_a among the producers (eventually the authority can decide to distribute the certificates for free, i.e. grandfathering). Still at time 0 producers use their knowledge on the distribution of D, i.e. the demand of electricity, compare it with H and, considering their production costs, fix their bid price function of electricity $p(D)$. Besides they also determine the optimal capacity expansions Q_{nc}^* and Q_c^*. The capacity expansion is immediately put in place and ready to operate. At time 0^+ the level of demand is revealed. The price of the emission certificates resolves either to 0 or f in $t = 0^+$ and remains constant until T. Costs, revenues, and all the cash settlements take place in T.

3 Emission allowances

By arbitrage arguments, it is possible to show that the time 0 price of a certificate is

$$p_a = fE\left[1_{[H,\infty)}\left(D - Q_{nc} - Q_{nc}^*\right)\right], \tag{1}$$

where f is the penalty fixed by the authority for every tonne of CO2 emitted without having a certificate. In short, the previous equation tells us that p_a is proportional to the probability that the power production required to conventional plants $(D - Q_{nc} - Q_{nc}^*)$ will exceed the 'covered production' (H). This implies that in T there will be not enough certificates to cover all the emissions, and that some producers will have to pay f for every tonne of CO2 remained uncovered.

It is evident form the previous formula, that the authority has a large impact on the price of the certificates, since it decides both the values of f and H. Producers will also influence p_a since they will decide the value of Q_{nc}^*.

4 Merit order and equilibrium price of electricity

According to standard market rules, the supply of electricity on the market is organized based on a merit order, that is lower bids are accepted first. Given the two technologies considered here, it can be easily shown that the power supply by RES plants (given their virtually null variable costs) will always have a priority with respect to the power supplied by conventional plants. In other words, conventional plants will be asked to generate electricity only if the supply of RES plants will not satisfy the demand. Given the hypothesis of a competitive market, any producer will offer on the market all its production capacity at a price equal to its marginal costs.

5 Policy regulator

We consider the problem of a policy regulator aiming at maximizing a social welfare function. A simpler and alternative objective function can be adopted, consisting in minimizing the risk that emissions will exceed a given target. In this case the control variable is represented by the number of emission certicates to issue at time 0.

Since we adopt the assumption that the demand of electricity is exougenous and has a positive probability to be arbitrary high, the event that the system goes short of certificates can not be eliminated. However, leveraging on the number of certificates issued and the level of the penalty, the authority influences the decision of the producers to expand the capacity of RES plants. RES plants represent the way to meet the demand of electricity avoiding emissions. Expanding the capacity of RES plants to a percentage sufficient to eliminate (or largely reduce) the risk that the system exceeds a given target, can be assumed as the fundamental objective of a cap-and-trade system such as the EU ETS.

6 Power producers and representative agent

We face here the problem of a set of electricity producers wishing to maximize their expected profits. As anticipated, the decision variables are the expansion capacities of the two types of technology, Q^*_{nc} and Q^*_c. These quantities can be negative.

However, instead of considering each producer individually, we model all of them through a representative agent. This agent acts, with respect to the expansion capacity problem, like an individual owing all the plants. Such a model corresponds to a situation where all the individuals transfer the expansion decision of their plants to an agent, which guarantees to maximize the expected profit of the entire power sector. Considering the relatively high concentration of the electricity market, the active role of industry associations and lobbies and the strategic nature of capacity expansion problems, the representative agent can mimic reasonably well the aggregate behavior of the power sector. As already said, this agent will decide as if it was the owner of all the plants, neglecting how its expansion decisions will be distributed among the individual producers. Unless explicitly said, the quantities Q_{nc}, Q^*_{nc}, Q_c, and Q^*_c will always be understood as the old and new (aggregated) capacities of the representative agent.

We stress again that the representative agent model is not applied to the production problem nor to fix the electricity prices. Such decisions remain under the individual control, based on the mechanics of the uniform price auction and the merit order introduced before, which correspond to a competitive market model usually adopted in the literature.

6.1 Profit function

Depending on the level of the demand revealed in $t = 0^+$, we can distinguish three possible outcomes for the profit G.

The first case (E_1) is when the demand is entirely satisfied with non-conventional plants, that is when $D - Q_{nc} - Q^*_{nc} \leq 0$. In this case the price of emission certificates falls to zero. The profit of the representative producer is negative, since the electricity is priced at the marginal cost (which is virtually zero for non-conventional plants). The power producers just face fixed costs (FC) and the (useless) expense of the initial buying of emission certificates:

$$G|E_1 = -FC - c_a \left(Q_c + Q^*_c\right).$$

In the second case (E_2), the level of the demand requires the contribution of non-conventional plants and yet all the emissions involved are regularly covered. More precisely this case happens when $0 < D - Q_{nc} - Q^*_{nc} < H$. Again the price of the emission certificates falls to zero. The equilibrium price of electricity is now driven by the marginal costs (mainly fuel consumption) of the conventional plants:

$$p = c_{v,c}.$$

We now have a positive component of profit, generated by the non-conventional production, which is sold at price p:

$$G|E_2 = -FC - c_a \left(Q_c + Q^*_c\right) + \left(c_{v,c} - c_{v,nc}\right)\left(Q_{nc} + Q^*_{nc}\right).$$

Notice that conventional production carries no profit, since it is sold at a price equal to the production costs.

Finally, we have a third event (E_3) where $D - Q_{nc} - Q^*_{nc} > H$. In this case conventional plants use all the available certificates and eventually some producers will have to pay the penalty f for the uncovered tonnes of CO2. By arbitrage arguments, the price at $t = 0^+$ of the emission certificates jumps to f and the price of electricity to $f + c_{v,c}$. In this case the profit is:

$$G|E_3 = -FC + \left(f - c_a\right)H + \left(f + c_{v,c} - c_{v,nc}\right)\left(Q_{nc} + Q^*_{nc}\right). \tag{2}$$

Notice that the conventional production now generates a unit profit equal to $f - c_a$. The uncovered conventional production $(D - Q_{nc} - Q^*_{nc} - H)$ is sold at the same price of its marginal cost $(f + c_{v,c})$, so it generates no profit. Needless to say, this third case is the most profitable one.

Fixed costs contain different components, mainly labor, maintenance and depreciation/investment, and can be linked to the size of the plants. We assume the following:

$$FC = c_{f,c}\left(Q_c + Q^*_c\right) + c_{f,nc}\left(Q_{nc} + Q^*_{nc}\right) + \alpha\left(Q_{nc} + Q^*_{nc}\right)^2,$$

where

- $c_{f,nc}, c_{f,c}$ are the unit investment costs (per MWh) of non-conventional and conventional plants,

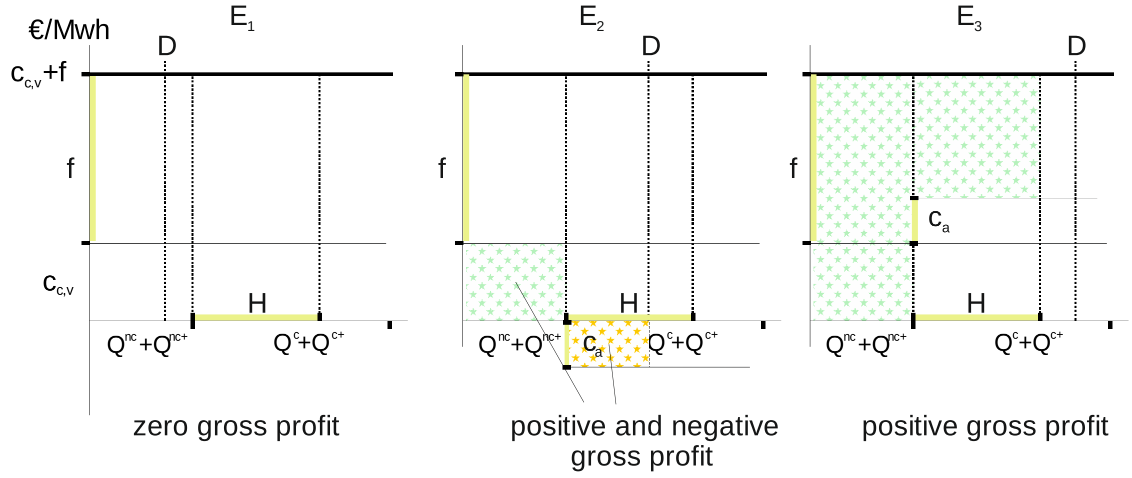

Figure 1: Aggregate (gross) profits of the three events.

- non-conventional plants are subject to convex increasing unit costs due to the fact that such plants are first located on the most efficient areas (regulated through coefficient α).

Figure 1 represents the aggregate (gross) profits, depending on the three events.

It can be observed that we do not consider the case $D - Q_{nc} - Q_{nc}^* = H$. Indeed we neglect this unlikely singularity, since in that case the price of emission certificates is not defined uniquely (i.e. it could take any value between 0 and f), which is a complication with no added value to our dicussion. The probabilities of the three events can be calculated assuming a known distribution (along with its parameters) for D. Assuming that D is distributed as normal random variable with mean μ and standard deviation σ, it is straigthforward to obtain the expression of the expected profit for the agent:

$$\begin{aligned}
E(G) = &-\Big(c_{f,c}\,(Q_c + Q_c^*) + c_{f,nc}\,(Q_{nc} + Q_{nc}^*) + \alpha\,(Q_{nc} + Q_{nc}^*)^2\Big) \\
&- c_a \min(H, Q_c + Q_c^*) \\
&+ c_{v,c}\,(Q_{nc} + Q_{nc}^*) \times \frac{1}{\sigma\sqrt{2\pi}} \int_{Q_{nc}+Q_{nc}^*}^{Q_{nc}+Q_{nc}^*+H} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx \\
&+ (f \min(H, Q_c + Q_c^*) + (f + c_{v,c})(Q_{nc} + Q_{nc}^*)) \\
&\times \left(1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Q_{nc}+Q_{nc}^*+H} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx\right)
\end{aligned}$$

6.2 Windfall profit

It is worth decomposing the gross profit into two parts: operational and windfall profit. In our simplified framework such decomposition is possible only for event E_3. In this case we can observe that, starting from Eq. (2), we have:

$$\begin{aligned} G|E_3 + FC &= (f - c_a)\,H + (f + c_{v,c} - c_{v,nc})\,(Q_{nc} + Q^*_{nc}) \\ &= \underbrace{(c_{v,c} - c_{v,nc})\,(Q_{nc} + Q^*_{nc})}_{\text{operational p.}} + \underbrace{f\,(Q_{nc} + Q^*_{nc} + H) - c_a H}_{\text{windfall p.}}, \end{aligned}$$

that is the gross profit $G|E_3 + FC$ consists of the gain from selling clean electricity at the marginal cost of the polluting plants (operational profit), plus the gain resulting from charging the cost of emission certificates at f, a price which is different from their purchase cost (windfall profit). In the case of event E_2 the selling price of emission certificates drops to zero, so no windfall profit obtains for the producers. Indeed they actually record a negative component of their gross profit:

$$G|E_2 + FC = \underbrace{(c_{v,c} - c_{v,nc})\,(Q_{nc} + Q^*_{nc})}_{\text{operational p.}} - \underbrace{c_a H}_{\text{cost of certificates.}} \quad .$$

In the case of event E_1 there is no gross profit at all.

As it is frequent to find in the literature, some authors tend to neglect windfall profits. At the origin of this course of action there is the concept of opportunity cost. Such authors consider that the true cost of the emission certificates is not the historical one, that is the monetary value spent at the moment of their purchase. They rather observe that in the moment c certificates are “used” to cover the production of 1 MWh, power producers lose the opportunity to sell them a the current market price. In that way, every MWh generated through the polluting plants balances perfectly cash inflow and opportunity costs, and motivates it exclusion from the calculation of profits.

In this paper we do not follow such view. The main reason of our position is that, comparing cash flows (such as those originated by the revenues from the sale of electricity) with non monetary values (such as opportunity costs) leads to an inconsistent calculation of profits.

7 The expansion problem for a power producer

We introduce the distribution of the demand of electricity (D) into the picture. This random variable is responsible of the event that will actually occur, among the three that we have discussed so far. Before entering into the precise equations of the expected profit, it is important to get of a clear understanding of the crucial link between the expansion decision (of RES technology), the density function of D, and the probabilities of the three events. The following Figure 2 highlights the interaction among these elements.

The problem of the power producer can be formalized as

$$\begin{gathered} \max_{Q^*_{nc},Q^*_c} E(G) \\ \text{s.t.} \\ Q^*_{nc} > -Q_{nc} \\ Q^*_c > -Q_c, \end{gathered}$$

and can be extended in various way (e.g., presence of budget constraints, risk contraints, etc.).

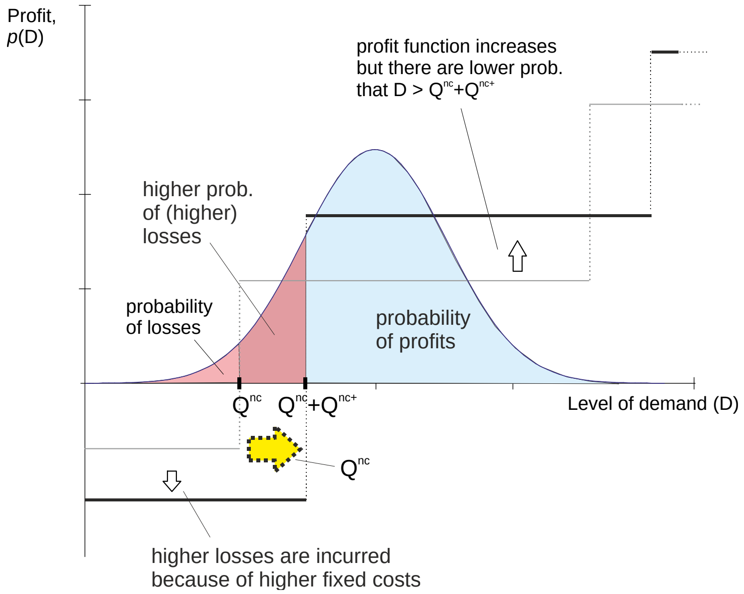

Figure 2: Expansion decision (of RES technology), density function of D, and probabilities of the three events.

The analytic expression of the derivative of $E(G)$ with respect to Q_{nc} is

$$\frac{\partial E(G)}{\partial Q^*_{nc}} = -c_{f,nc} - 2\alpha\left(Q_{nc} + Q^*_{nc}\right) + \frac{\min(H, Q_c + Q^*_c)mf}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{Q_{nc}+Q^*_{nc}+H-\mu}{\sigma}\right)^2}$$

$$+(c_{v,c} - c_{v,nc})\left(\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\frac{Q_{nc}+Q^*_{nc}+H-\mu}{\sigma}} e^{-\frac{1}{2}x^2}dx - \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\frac{Q_{nc}+Q^*_{nc}-\mu}{\sigma}} e^{-\frac{1}{2}x^2}dx\right)$$

$$+\frac{(c_{v,c} - c_{v,nc})(Q_{nc} + Q^*_{nc})}{\sigma\sqrt{2\pi}}\left(e^{-\frac{1}{2}\left(\frac{Q_{nc}+Q^*_{nc}+H-\mu}{\sigma}\right)^2} - e^{-\frac{1}{2}\left(\frac{Q_{nc}+Q^*_{nc}-\mu}{\sigma}\right)^2}\right)$$

$$(f + c_{v,c} - c_{v,nc})\left(1 - \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\frac{Q_{nc}+Q^*_{nc}+H-\mu}{\sigma}} e^{-\frac{1}{2}x^2}dx\right)$$

$$-\frac{(f\min(H, Q_c + Q^*_c) + (f + c_{v,c} - c_{v,nc})(Q_{nc} + Q^*_{nc}))}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{Q_{nc}+Q^*_{nc}+H-\mu}{\sigma}\right)^2}.$$

To find the stationary points of $E(G)$, the solutions of $\frac{\partial E(G)}{\partial Q^*_{nc}} = 0$ and $\frac{\partial E(G)}{\partial Q^*_c} = 0$ can be worked out numerically.

8 Conclusions

The policy of reducing emissions by means of cap-and-trade systems has an intrinsic flaw, at least when it is applied to markets with a high pass-through coefficient of production costs, such as electricity markets. In particular, it generates at the same time both an incentive to expand environment friendly technologies and an incentive to keep in place a large portion of traditional polluting plants. Moreover, serious efficiency concerns arise when the expansion of the green capacity is genuinely attributable to cap-and-trade systems. Indeed when the number of certificates is low enough to rise significantly the cost of emission certificates, large and unjustified windfall profits develop in favor of producers, at the cost of consumers. Surprisingly, in such case, the impact of cap-and-trade systems on the expansion of green technologies is most of the times even recessive (i.e. larger exapansion of the RES technology would take place if no cap-and-trade was there).

The model proposed here shows both analytically and numerically these strong results. The origin of the deep difference of our results from those of the classic work of Montgomery lays in the inclusion in our analysis of the impact of emission costs on the price of the final product (i.e. electricity in this paper), while Montgomery's analysis fundamentally takes the output price as a fixed parameter.

In this paper a key assumption is that the expansion decision of the plants is taken "as if" all the producers had given a mandate to a representative agent to decide for them with the objective of maximizing the expected profit of the entire power sector. Such a long sighted and strongly cooperative behavior can be justified considering the high level of concentration in some markets, such as the electricity market, and the active role played the industry associations. However, even in the case of the electricity market such hypothesis is not completely realistic. Introducing a competitive segmentation among producers, such as small size and large size producers, can be expected to have a relevant effect on the results. So an interesting extension of the present analysis will be that of modeling the capacity expansion decision as a game among two or more competitive segments of producers.

Besides, modifying the time framework of this model from one period to multiperiod or continuous time will also bring more realism to the analysis. This in turn will allow the model to be empirically tested and possibly applied to improve some regulatory policies, such as those urgently expected for the EU ETS.

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