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The zero-emission certificates: A novel CO_2-pollution reduction instrument applied to the electricity market

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Abstract

Today several instruments exist to decrease air pollution. The paper discusses pollution taxes, emission trading permits and green certificates applied to reduce the CO_2-emissions in the electricity sector. It then investigates how the different mechanisms behind these three instruments can possibly be combined. The proposed approach is to introduce the concept of zero-emission certificates (ZEC). ZEC are confirming actual emission reductions achieved by electricity producers as compared to a well-defined baseline. Producers can trade ZEC on a market to achieve least-cost efficiency in their reduction efforts. Distributors can themselves produce an additional contribution to emission-reductions by decreasing the final demand, i.e., by producing zero-emission MWh. In this way the electricity market is approached from both the supply and the demand sides. The paper uses system dynamics to validate the approach. It shows why it is in the interest of all operators to make the largest possible reduction efforts as long as they are compatible with economic efficiency.

Keywords: System dynamics; Climate change; Taxes; Trading permits; Green certificates; Zero-emission certificates

1. Introduction

The decrease of greenhouse gases resulting from human activities has become a priority in many countries of the world. These gases, of which CO_2 is the most important, are a possible cause of the climate change, for which evidence has been accumulated by the UN-IPCC (Intergovernmental Panel on Climate Change; see Kyoto protocol, 1998). CO_2 mainly results from the burning of fossil fuel, i.e., coal, oil and natural gas used as the basic energy resources of the world.

This paper analyses instruments to promote the efforts of fewer CO_2-emissions in the electricity sector. With the notable exception of the considered electricity producing technologies, their characteristics and costs, no precise reference will be made to real situations of any country or economic union.

In Section 2 of the paper, we define the characteristics of three economic instruments created to assist this reduction process, and to promote efficiency (Hanley et al., 1997): the energy tax, also called carbon tax for obvious reasons; the

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CO_2-emission trading permits; and the green certificates (GC).

In Section 3 we introduce the concepts of zero-emission MWh (Megawatt-hours), zero-emission percentages (ZEP) and zero-emission certificates (ZEC) combining Demand Side Management with economically efficient substitution control on the supply side (SS).

In Section 4, we elaborate a system dynamics model of a global market in order to validate the described mechanisms. It will be shown how electricity producers, in interaction with the rest of the market through the exchange of ZEC, apply efficient substitution policies in order not to loose market shares. Distributors are shown to make an arbitrage between the purchase of ZE-MWh and the use of their own policy to decrease demand. It is also shown how the regulator can define economically sound reduction objectives.

Finally Section 5 presents some conclusions for the proposed instrument.

2. Existing instruments to induce emission reductions

2.1. The carbon tax

The objective of a carbon tax is to internalise the external cost of CO_2-pollution into the price of fossil fuels (Hanley et al., 1997). Such a pollution tax is an economically efficient mechanism to allocate efforts first to these activities with the lowest marginal pollution abatement costs. Calling T the value of the tax expressed in [EUR/kg CO_2], each operator on the SS will strive to minimise his tax imposition. In case the marginal cost of emission reductions is lower than T, it will be profitable to further decrease the CO_2-emissions. Should the marginal cost be on the contrary larger than T, it will be preferable to pay the tax. At equilibrium the tax T will be equal to the marginal pollution abatement cost. The operators with the lowest marginal costs will thus reduce most their emissions. On the demand side (DS) the carbon tax will shape the behaviour of consumers in using fossil fuels more rationally and efficiently (rational use of energy or RUE).

However, some practical difficulties are to be expected. First, the determination of the externality and therefore of the tax value T is difficult. Second, tax neutrality shall be achieved, by compensating decreases somewhere else in the economy. Third, a pollution tax is not specific, i.e., its revenues are not allocated to any special purpose but goes to the general State budget (it is not used for example to promote zero-emission power plants). Finally, the tax is part of the electricity price. The consumer, who is supposed to change his or her behaviour, will not be aware of it in a transparent way.

2.2. The emission permits

Each permit represents a fixed quantity of allowed CO_2-emissions, typically 1 metric ton per permit (IEA, 2001). The number of permits in hands represents the total permitted emission quantity; a penalty is applied in case the actual emissions are in excess of this quantity.

Permits may be traded. Buyers will be those operators or countries, which lack permits for their emission needs (their marginal costs of reduction are high). Sellers will be those operators or countries, which have permits in excess (their marginal costs are low).

An advantage of permits as compared to the energy tax is that the equilibrium price will be established by the equilibrium between supply and demand on the trading market.

There are several practical difficulties, however. First, several allocation schemes of permits between operators or countries are possible. One of the commonly considered schemes is called "grandfathering". The historical emissions are used as a redistribution key. But the question has brought important debates as to the fairness of this approach. Second, perversions in the system are possible. For example, some operators or countries may be collecting large quantities of permits for further resale, although no real reduction efforts have been made. This possibility is known as the "hot air" artefact (IEA, 2001). Finally, it is not clear till today how the penalties have to be charged to those operators or countries, which are short of permits as compared to actual emissions.

2.3. Green certificates

GC have been introduced by several governments to support the development of renewable energies (IEA, 2001; Odgaard, 2000; van den Berg and van Biert, 1998). The regulator imposes a quota as a percentage of the total electricity production, which has to come from those renewable sources. Wholesalers, distributors or retailers of electricity are liable to respect the quota. To give them more flexibility and compensate for missing green kW h, they can purchase GC from the green-electricity producers. The price of GC will be close to the difference in price between renewable electricity and 'classical' electricity. The additional revenues for the producers will compensate them for this difference in price. Distributors, which do not achieve the quota imposed by the regulator, will have to pay penalties.

GC are not subject to the same fairness debates as permits: no certificates can be produced without actual electricity production, in contrast with the "hot air" artefact.

There are also some practical difficulties, however. First, the start up of the GC market is difficult in countries with small initial renewable capacities, as shown by Kunsch et al. (2002). Second, although the renewable quota is respected, or even exceeded, the emission-reduction objective might not be achieved. Renewable electricity could be used mainly to compensate the increase in demand and not to substitute "dirtier" emission sources. Finally, an important issue is the validity on an international scale of GC.

A GC market is based on comparable principles to the CO_2-emission permit, but in the present conditions, no exchange between these markets is possible. This is one of the reasons why we developed a combined instrument in this paper, called "zero-emission certificate", or ZEC.

3. Defining the zero-emission certificates as a combined instrument

3.1. Basic specifications of an emission-reduction instrument

First we discuss the basic properties of an adequate instrument for decreasing CO_2-emissions. The reference will be the electricity market. The way to extend the approach to other sectors of the energy market will be investigated in further papers. We adopt the following terminology:

- The electricity generators, called "producers" represent the SS.
- The distributors of electricity (wholesalers or retailers), and the final clients represent the DS. The distinction between distributors and final consumers is blurring out, as one day all customers will be eligible to buy electricity directly from producers inland or abroad (European Commission, 1996). To make things simple, the demand will be identified with distributors, dispatching electricity to a multitude of clients through their own distribution network.

The framework of implementation of a "good" emission-control instrument is defined within the following set-up:

- First, it appears that the development of clean production technology on the SS is not sufficient. Should the final demand continue to increase in an uncontrolled way, the objectives of CO_2-emission reductions will fail. Therefore it is necessary to locate the basic control mechanism in the field of DS-Management. This clearly implies the intervention of a regulator defining objectives, and also imposing penalties in case the objectives are trespassed.
- Second, the economic reality shall be recognised. Artificially ambitious reduction objectives will necessarily be counterproductive. This can happen with the use of GC-quotas, which rely on the development of renewable technologies, far from being competitive in many countries. Reduction objectives should not result from

arbitrary decisions of regulators, but should reflect the real substitution possibilities of electricity producing companies.

- Finally, the least-cost objective must keep its validity. Therefore SS-management shall also be practised, i.e., the producing market shall not be unreasonably regulated, nor made so completely constrained against economic efficiency. Trading emission permits is a good way for achieving this efficiency.

3.2. The contributions of supply and demand in the emission decrease

The total decrease of CO_2-emissions in time t, called further on simply "emissions", from a baseline-emission level B_s of the SS can be described as follows:

$$\Delta e(t) = W(0)B_s - W(t)S(t) \tag{1}$$

where $\Delta e(t)$ is the decrease of emissions from B_s in time t [kg CO_2/year]; $W(0)$ is the total demand of electricity in $t = 0$ [MWh/year]; $W(t)$ is the total demand of electricity in time t [MWh/year]; B_s is the baseline specific emission rate in the supply sector [kg CO_2/MWh]; $S(t)$ is the specific emission rate of the producing capacity in t [kg CO_2/MWh]. Note that (1) can be further developed to give

$$\begin{aligned}\Delta e(t) &= W(0)[B_s - S(t)] + S(t)[W(0) - W(t)]\\ &= B_s W(0)\{p_s(t) + [1 - p_s(t)]\Delta d/W(0)\}\end{aligned} \tag{2}$$

where $p_s(t) = 1 - S(t)/B_s$ [%] is the percentage decrease in the specific emission rate of the producing power plants in time t, with respect to the baseline B_s; $\Delta d(t) = W(0) - W(t)$ [MWh/year] is the decrease in demand from $t = 0$ to time t.

So the percentage total decrease in emission rate in time t, we call p_e, can be written as the sum of two terms as follows:

$$\begin{aligned}p_e(t) &= \Delta e(t)/[W(0)B_s]\\ &= p_s(t) + [1 - p_s(t)]p_d(t) \ [\%]\end{aligned} \tag{3}$$

where $p_d = \Delta d(t)/W(0) = 1 - W(t)/W(0)$ [%] is the percentage decrease in the total demand of electricity from $t = 0$ to time t.

The first term on the right-hand side (RHS) of Eq. (3) corresponds to the contribution of *producers* in the efforts to reduce emissions with respect to the constant baseline, by substituting less polluting technology to more polluting technologies, and in general by modifying their power mix in favour of fewer emissions.

The second term on the right-hand side in Eq. (3) corresponds to the contributions of *distributors* in their efforts to reduce the final demand, for example by promoting RUE by their final clients.

The total potential for reduction is represented by those two contributions, to be considered as a single reduction objective by the regulator. Splitting the latter in two, imposing one objective to production, and one to demand would only give a partial result. Moreover it would be very difficult, if not impossible, to achieve. It is why the imposition (3) should be made to the DS only. Also the penalty for non-respect shall be entirely on the DS, and not at all on the SS.

In addition a very important remark has to be made. To be meaningful, the definition of (3) must be compatible with the real economic possibilities of supply and demand. A generally unfeasible "wishful thinking" of regulators or politicians has to be avoided. It will be shown later how this can be done in practice. A first observation is that a crucial aspect is the definition of the baseline, which proves to be delicate for implementing polluting permits.

3.3. The economic incentives and strategies to reduce emissions

Regulators' strategies shall anticipate the economically feasible evolution defined by Eq. (3), and define reasonable objectives for emission decreases accordingly. This statement can be made more formal for both the SS and DS.

3.3.1. The substitution and ZEC strategy on the supply side

The potential for reductions on the SS stems from the substitution potential of dirtier technologies by cleaner ones. Companies making the biggest substitution effort should be rewarded by increased market shares.

Consider one of the producer, we call "Producer 1", contributing to satisfying part of the demand of distributors. The objective is to calculate the total emissions of this producer and their evolution with respect to a baseline to be defined.

Given are for "Producer 1": $W_1(0)$ the total produced energy in $t=0$ [MWh/year]; $W_1(t)$ the total produced energy in t [MWh/year]; B_1 the baseline specific emission rate [kg CO_2/MWh]; $S_1(t)$ the specific emission rate of the producing capacity in t [kg CO_2/MWh]; and $\Delta e_1(t)$ the decrease of emissions from $t=0$ to time t [kg CO_2/year]. The following equation applies:

$$p_1(t) = 1 - S_1(t)/B_1 \ [\%] \tag{4}$$

where p_1 is the percentage decrease of specific emissions of "Producer 1" from the baseline.

A specific baseline for "Producer 1" must have a general validity in the market. Choosing a CO_2-emission level at a given moment in time, like the 1990-emission level selected as a baseline in the Kyoto protocol (1998) is completely artificial and is not related to the SS capabilities. Some producers might have made big effort before 1990, and they would not be rewarded in the future for their additional efforts. It is why it is proposed to elicit a universal and timeless benchmark as the worst-case possibility for the CO_2-emissions. An attractive possibility is to choose specific emissions from old-fashioned coal-power plants around 800 kg/MWh, assuming that most modern generating plants can do better. In this way, it is easy to evaluate where each producer will be, at any time, with respect to this worst case.

In this way, the baseline of "Producer 1" is identical with the baseline of the SS:

$$B_1 = B_s; \quad p_1(t) = 1 - S_1(t)/B_s = \text{ZEP}_1(t) \ [\%]. \tag{5}$$

Note that p_1 has a simple physical interpretation: given the baseline emission rate B_s, p_1 gives the equivalent proportion of zero-emission power plants in the mix to achieve the same reduction level from the chosen benchmark B_1 in time t.

For that reason, the authors decided to call $p_1(t)$, the *zero-emission equivalent percentage, or* ZEP_1 [%] of Producer 1 in the supply market. The ZEP_1-value gives a useful and universal indicator for measuring where this particular producer stays in the market with respect to the chosen baseline. Of course this concept is valid for each producer i on the SS.

As coal is abundant and coal-fuelled plants are generally considered as having the cheapest generating costs, there is a clear economic interpretation of ZEP_1. This percentage represents the investment effort made in the past by the producer 1 to move away from this most polluting to less polluting plants.

(Note that this interpretation has to be modified with respect to nuclear power plants. The latter are in present economic conditions still cheaper than coal and they have no emissions; the costs should include the CO_2-free externalities, however, which substantially increases the generating costs of nuclear electricity (see Kunsch, 2001)).

If Producer 1 produces in year t, $W_1(t)$ [MWh/year], his annual equivalent *zero-emission MWh* ('ZE-MWh') is given by the product $W_1(t) \times \text{ZEP}_1$:

$$\begin{aligned}(\text{ZE-MWh})_1(t) &= \text{ZEP}_1(t) \times W_1(t)\\ &= \#\text{ZEC per year [MWh/year]}.\end{aligned} \tag{6}$$

Assume now that, for certification purposes, Producer 1 receives from the regulators *ZEC*, each representing 1 zero-emission MWh, so that each year this producer would receive $(\text{ZE-MWh})_1$ ZEC.

A ZEC has a price, which is either 0 if the generating cost of "Producer 1" is below the generating cost of the baseline power, or is given by the positive difference in generating costs. The price (without margin) of the ZEC, if positive, will thus be given by the equation

$$P_{\text{ZEC}} = (C_s(t) - C_1^{(B)}(t))/p_1(t) \tag{7}$$

where $C_1^{(B)}$ is the generating cost of the baseline power plant [EUR/MWh] and $C_s(t)$ the average generating cost of the SS.

As a special case, Eq. (7) gives the price of GC for $p_1 = \text{ZEP}_1 = 100\%$ (see Section 2.3). So let us assume that a market is created for trading ZEC, and that the equilibrium price (7) is observed. "Producer 1" is in general too small to influence significantly the market price, and he will be price-taker. Buying ZEC at this price instead of substituting different plants to the obsolete power plants, might be an attracting alternative from the cost point of view. This will happen in case the ZEC-price is significantly below the marginal substitution cost.

In this case, the non-substituted ‘dirty’ MWh can still be kept ‘clean’ by purchasing from other producers a sufficient number of ZEC.

ZEC have with GC the common feature that they are given by the regulator to the producer free of charge, proportionately to the produced ZE-MWh. The calculation of the number of distributed ZEC can be based on the average consumption of fuel for each power plant in the mix: a suitable accounting can easily be set in place by the regulator.

Fig. 1 shows the SD influence diagram of the substitution strategy of “Producer 1”, as an example for any producer. On top of the diagram a chain of three stocks represents the life cycle of power plants from planning to decommissioning after their average lifetime has been completed. The lower right part shows the calculation of the emissions and of the ZEP_1 according to Eq. (6). The central left part shows the substitution strategy of plants completing their lifetime to be described now.

A natural way is to substitute obsolete plants with modern plants with fewer emissions. An alternative course of action is to retrofit some plants to have them less polluting. This approach is equivalent to substitution, given the necessary additional investment. A meaningful substitution shall of course bring an emission decrease. A zero-emission power source will be replaced by itself, or by a less expensive one from the same technology.

As a simplification of the model, it will be considered that withdrawing power at a faster pace than imposed by obsolescence is not considered as being economically attractive. Of course, in case his market share is changing, “Producer 1” will have no choice than to adjust his production. A simple way to do, in case of a production decrease,

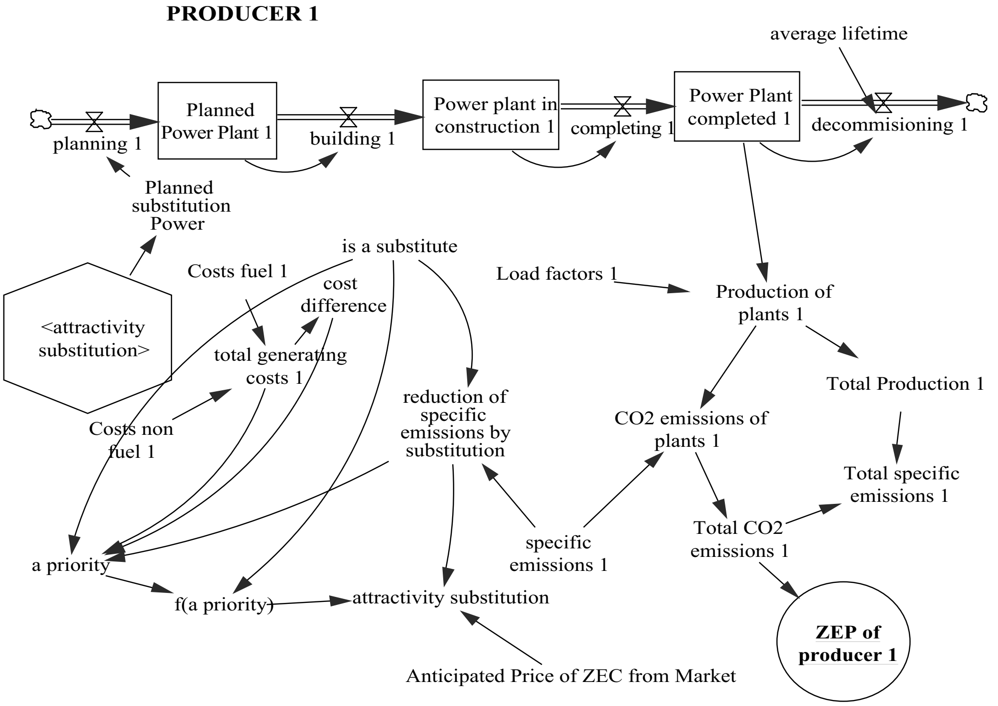

Fig. 1. Influence diagram showing the substitution process of obsolete plants by less-polluting ones leading to an improved ZEP of “Producer 1”.

is to withdraw first more-emitting plants; or to give priority to investing in less-emitting plants in the opposite case.

In order to define the principles of meaningful substitution strategies, some new time-dependent variables are now introduced. It is considered for simplicity that they are common to the whole market, so that no subscript indicating the producer is present. Define $S^{(k)}(t)$ the specific emission of the production source (k) to be substituted [kg CO_2/year]; $S^{(k,l)}(t)$ the decrease in specific emission of the production source (k) when substituting with the source (l), (0 in case of an increase) [kg CO_2/year]; $C^{(k)}(t)$ the marginal production cost of production source (k) [EUR/MWh]; $C^{(k,l)}(t)$ the positive difference in marginal production cost when the production source (l) is substituted to source (k), (0 if this difference is negative) [EUR/MWh]; $O^{(k)}(t)$ the power of production source (k) becoming obsolete in t [MW/year]; $A^{(k,l)}(t)$ the attractivity index of source (l) substituting (k) [Dmnl] (to be defined in Eq. (8)).

Given that, at time t, a power $O^{(k)}(t)$, originating from production source (k) has to be decommissioned, the attractivity of any possible substitute (l) of (k) can be defined as follows:

$$A^{(k,l)} = S^{(k,l)}/S^{(k)} f\{[C^{(k,l)}/C^{(k)}]/[S^{(k,l)}/S^{(k)}]\} \tag{8}$$

where $f(\cdot)$ is a monotonously decreasing function being equal to 1, when its argument is 0, and decreasing rapidly to zero when its argument increases.

This equation lets appear that a substitution source will be increasingly attractive with the actual decrease in emissions it can bring (first factor on the RHS). The cost of this decrease is also taken into consideration in the second factor.

As visible in the lower central part of Fig. 1, the attractivity of purchasing ZEC rather than substituting plants is also brought into balance. The attractivity of ZEC purchase is computed from the adapted Eq. (8). Given that $S^{(k,l)} = S^{(k)}$ if the strategy l corresponds to keeping power plants k and buying ZEC instead of substituting, the attractivity of ZEC is given by

$$A^{(k,\mathrm{ZEC})} = f(P_{\mathrm{ZEC}}/C^{(k)}) \tag{9}$$

where the ZEC price P_{ZEC} is defined in Eq. (7).

In face of the influence diagram of Fig. 1 the sensible question may be raised what is the incentive of 'Producer 1' to substituting obsolete plants by more expensive plants. Indeed the regulator will impose any reduction objectives to the DS, but not to the SS, as shown in Section 3.2.

The reason why substitution of obsolete capacity will take place is competition. In a monopoly market producers would have no reason to comply with their share of the burden represented by $p_s(t)$ in the first term of Eq. (3). In the competitive market today in creation for example in Europe, 'Producer 1' will have to face the risk that his clients will turn over to competition. They would do so if the prices of electricity are too high, but also in case the value $\mathrm{ZEP}_1 = p_1(t)$ defined in Eq. (5) is significantly smaller than the market average $\mathrm{ZEP}_s = p_s(t)$. 'Producer 1' will therefore apply the strategy described in Fig. 1. Either he will substitute obsolete plants with important emissions by cleaner ones, or he will buy ZEC on the market, in case their price is significantly smaller than his marginal costs of substitution. In the later simulation it will be shown that the market share of "Producer 1" will be dramatically declining in case price_1 and ZEP_1-level are significantly different from their average market values.

3.3.2. The strategy on the demand side

No important bias is introduced in the model if it is assumed that the whole DS is collapsed into one single distributor purchasing electricity from the SS.

Coming back once more to Eq. (3), it is seen that the second term on the RHS represents the contribution of the distributor. The 'economically meaningful demand decrease' is represented by the factor $p_d(t)$, the percentage decrease in the total demand for electricity from $t = 0$ to t.

Fig. 2 represents the SD influence diagram of the demand reduction strategy of the distributor. The 'economically meaningful demand decrease' from the initial demand is determined by arbitrage between the marginal costs of reducing the demand and the 'planned average electricity price'. This price is computed from the trend function of the average total generating costs for a given planning horizon. The result of the arbitrage is

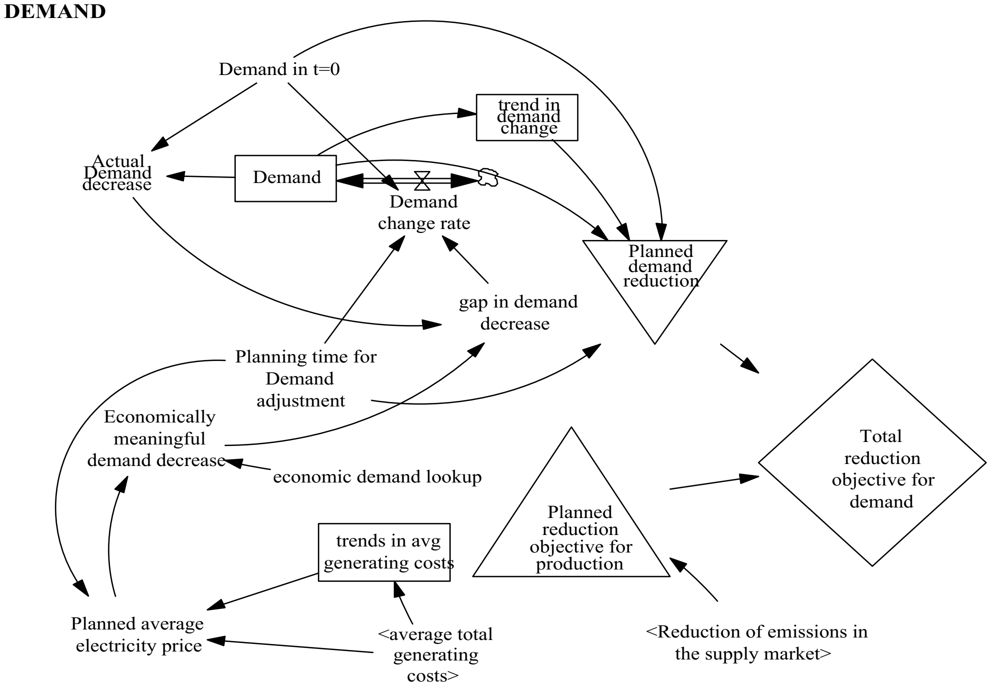

Fig. 2. The result of the cost arbitrage process on the DS between the marginal cost of demand reduction and the “planned average electricity price” of electricity bought from the SS is given by the table “economic demand lookup”. Forecasting reduction trends from both DS and SS provides the total CO_2-reduction objectives. In this way the objective imposed to the DS is economically meaningful for the whole market.

given as a percentage decrease by the lookup table ‘economic demand’.

More formally this result is equivalent to solving the following implicit equation in the percentage decrease in the total demand $p_d(t)$ to obtain

$$C_d[p_d(t+T_d)] = C_M(t+T_d)(1+m) \tag{10}$$

where t represents the current time; $C_d(\cdot)$ represents the marginal costs of decrease in the electricity demand in t from the conditions in $t=0$ [EUR/MWh]); T_d represents the ‘planning time for demand adjustment’ [time]; $C_M(t+T_d)$ represents the expected average market generating cost in time $(t+T_d)$ [EUR/MWh], calculated by extrapolating the current trend; $(1+m)>1$ represents the dimensionless margin factor to be applied to this generating cost to obtain the ‘planned average electricity price’.

The solution of Eq. (10) gives the ‘economically meaningful demand decrease’ [MWh/year] ED = p_d to be achieved in the planning horizon $(t+T_d)$. From there, the ‘demand change rate’ DR, also visible in Fig. 2, can be calculated with a proportional control feedback loop using the ‘gap in demand decrease’:

$$\begin{aligned}\mathrm{DR}(t) &= (\mathrm{ED}(t)-\mathrm{DD}(t))/T_d \\ &= \text{‘gap in demand decrease’}/T_d\end{aligned} \tag{11}$$

where DR(t) is the demand change rate [MWh/(year × year)]; DD(t) is the actual demand decrease in t from $t=0$ [MWh/year].

Fig. 2 also shows how the regulator will determine by extrapolating real trends the ‘total reduction objective for demand’. The latter is given as the sum of the two terms ‘reduction of emissions in the supply market’ from the SS and ‘planned demand reduction’ from the DS respectively. Herewith the economically viable reduction opportunities of both SS and DS are reliably determined in prospective.

3.3.3. Rules of the ZEC-market

The facial value of one ZEC is equal to one zero-emission MWh. Each year the quantity of ZEC delivered free of charge by the regulator to the whole SS is thus equal to the produced ZE-MWh [MWh/year]. The SS uses ZEC as certification instruments for the quality of electricity for what regards emissions. Trading within the SS is possible to achieve economic efficiency as described in Section 3.3.1 and Fig. 1.

Calling $O_{\mathrm{ZE}}(t)$ [MWh/year] the 'total reduction objective for demand', determined as explained in Section 3.3.2 and Fig. 2, Eq. (3) and the definitions in Eq. (6) give

$$\begin{aligned} O_{\mathrm{ZE}}(t) &= \{p_{\mathrm{s}}(t) + [1 - p_{\mathrm{s}}(t)]p_{\mathrm{d}}(t)\}D(t) \\ &= \text{ZE-MWh} = \text{ZEC per year}(t) + [D(t) \\ &\quad - \text{ZEC}(t) \text{ per year}]p_{\mathrm{d}}(t) \ [\text{MWh/year}]. \end{aligned} \tag{12}$$

The presence of many agents on both SS and DS will guarantee adequate collective behaviour as in the aphorism of the invisible hand:

Producers, who are not in line with the market with respect to costs and specific emissions, taking into account the purchase of ZEC, will loose significant part of their market shares. In normal conditions managers would want to avoid that. For example if "Producer 1" has a ZEP_1 above the average market $\mathrm{ZEP}_{\mathrm{M}}$, an unfavourable dimensionless attractivity gap will appear:

$$\begin{aligned} &(\text{Attractivity gap})_1(t) \\ &\quad = A_{\mathrm{M}}(C_{\mathrm{M}}(t), \mathrm{ZEP}_{\mathrm{M}}(t); t) - A_1(C_1(t), \mathrm{ZEP}_1(t); t) \end{aligned} \tag{13}$$

where A stands for the attractivity, defined in a way similar to Eq. (8); C's with their respective index for market (M) or "Producer 1" (1) stand for the generating costs [EUR/MWh]. To close the attractivity gap, and not to be wiped out from the market, "Producer 1" can either buy ZEC on the trading market or change his current power mix to a less polluting one, whatever is cheapest. The producers who have ZEC in excess will welcome an additional financing source for promoting their more efficient but dearer power mix.

Distributors would be scared to incur a significant penalty: they will verify that they do sufficiently with respect to the existing RUE-techniques and best efficiency of use of electrical equipment. Although it is hoped for that the penalty will almost never be applied, it should be large enough compared to the MWh price to be efficient as a deterrent for trespassing. It is suggested to have the penalty twice this price for each missing ZEC with respect to the overall objective O_{ZE} as defined in Eq. (12), so that for a 'Distributor 1':

$$\begin{aligned} &(\text{Missing ZE-MWh})_1 \\ &\quad = \max[0, O_{\mathrm{ZE}}(t) - (\text{ZE-MWh})_1] \ [\text{MWh/year}]. \end{aligned} \tag{14}$$

In practice the missing ZE-MWh would not be computed instantaneously, but rather smoothed over several years, and intermediate warnings would be issued in case of a persistent attractivity gap.

4. A simulation model with system dynamics

4.1. Main assumptions of the model

The following model presents a simulation using the system dynamics technique (Richardson and Pugh, 1981) of the way a ZEC market would function. It has a SS represented by a global supply market containing an individualised "Producer 1" pictured in Fig. 1 (about 8% market share), and a global DS, pictured in Fig. 2.

Individual distributors on the DS are assumed to react under the threat of penalties entirely in the way described in Section 3.3.2. This has the result that all will adopt the strategy of least cost, by having their marginal emission-reduction costs matching the marginal price of electricity.

"Producer 1" and the other producers in the supply market are assumed to use a substitution strategy of obsolete plants as described in Section 3.3.1 and Fig. 1. Their respective power mix and the power mix of the whole SS are indicated in Table 1. Six types of power plants (PP) are considered for electricity production: (1) ordinary coal PP, (2) zero-emission coal PP (ZEPP), (3) steam and gas turbine PP (STAG), (4) combined heat-power PP (CHP), (5) Wind turbine PP onshore (WINDON), (6) Wind turbine offshore (WINDOFF). On one hand, the individual "Producer 1", represents about 8% of the demand, and, on the other hand, another large producer represents the other 92% but with a rather different power mix (less coal, more gas and some renewable electricity).

The possibilities of substitution between different PP are indicated in Table 2. Zero-emission plants are (2), (5), (6) and are replaced by PP of the same kind only. All technical and economic data are coming from the report of the so-called Ampère Commission (2000) entrusted by the Belgian government to make a prospective study on the future electricity market in Belgium.

It is assumed that the economically sound market evolution is used as the emission-reduction benchmark as described extensively in the Section 3 of this paper. Furthermore ZEC are traded on a market assumed to clear exactly at all time. Due to his power mix comparatively to the whole supply market, "Producer 1" is potentially buyer of the excess ZEC coming from the rest of the SS. The latter is brought to its equilibrium by internal transactions, invisible in the model, as shown in Fig. 1. The ZEC price is determined according to formula (7) in Section 3.3.1.

4.2. Analysed scenarios and main results

Several runs are presented using the system dynamics simulation code VENSIM DSS2 Version 3.0.B (1997):

The first run illustrates the functioning of the ZEC-market for producers, according to the influence diagram of "Producer 1" shown in Fig. 1.

The total demand and the market share of "Producer 1" are assumed to be constant. The substitution strategy of "Producer 1" is investigated in the absence of a ZEC-market in Fig. 3. It shows that the decrease of ordinary coal (ORDCOAL) is rather drastic. The substitution starts with zero-emission coal power plants (ZEPP), continues with gas (STAG and CHP) and renewable wind energy.

Fig. 4 shows how the substitution strategy can be influenced by the possibility of exchanging ZEC with other operators on the markets. The

Table 1
Production mix [% MWh] of "Producer 1" and of the SS as a whole

Production (%)	COAL (%)	ZEPP (%)	STAG (%)	CHP (%)	WIND ON (%)	WIND OFF (%)	Market share (%)
Producer 1	79	0	16	5	0	0	8
Whole SS	17	0	66	8	3	6	100

Table 2
Characteristics of substitution within the power mix of "Producer 1"

Production	COAL	ZEPP	STAG	CHP	WIND ON	WIND OFF
Substitute specific emissions [kg CO_2/MWh]	805	0	343	232	0	0
Generating cost increase from coal [%]	0	26	2	16	129	72
ZEC	X	–	X	X	–	–
COAL	X	–	–	–	–	–
ZEPP	X	X	–	–	–	–
STAG	X	–	X	–	–	–
CHP	X	–	X	X	–	–
WIND ON	X	–	X	X	X	–
WIND OFF	X	–	X	X	–	X

Columns indicate the original production source; a possible substitute is indicated in the row through X. The ZEC substitute means that the capacity is not substituted but made to zero-emission by buying ZEC.

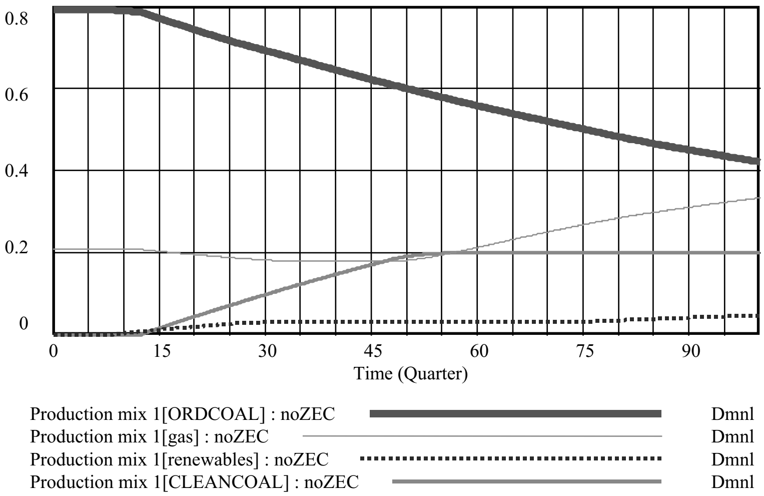

Fig. 3. Production mix of "Producer 1" in case the substitution policy is not influenced by the exchange of ZEC (ORDCOAL = ordinary coal; CLEANCOAL = coal burnt in zero-emission power plants ZEPP; gas = STAG + CHP; renewables = wind offshore and onshore).

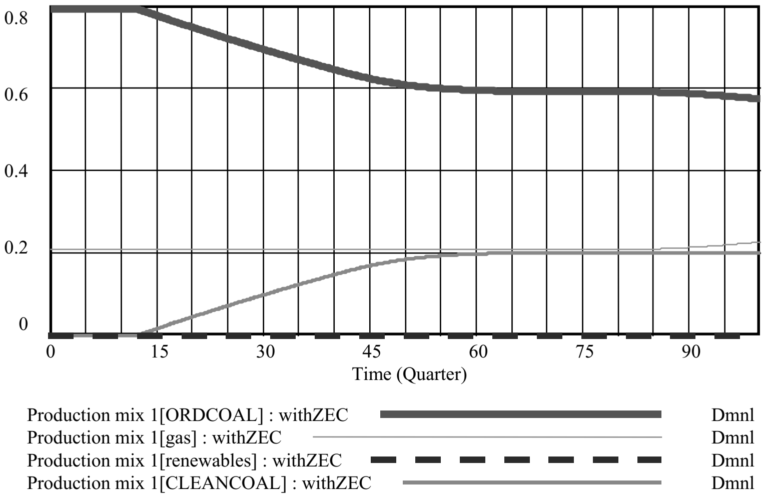

Fig. 4. Production mix of "Producer 1" in case the substitution policy is influenced by the exchange of ZEC with others producers, which have lower marginal costs of substitution. Much less ordinary coal is substituted (ORDCOAL = ordinary coal; CLEANCOAL = coal burnt in zero-emission power plants ZEPP; gas = STAG + CHP; renewables = wind offshore and onshore).

substitution of ordinary coal by gas is far less important, and renewable electricity is not used. Fig. 5 shows the economic gain for "Producer 1" of buying ZEC for the same purpose as it would purchase emission permits, in order to plan the substitution at the least cost. Although the generating costs are much lower in this particular case, the total gains (taking into account the purchase of additional ZEC to have the same ZEP as the whole SS) are positive, but relatively small. This is because the strategy of Fig. 4 requires the purchase of more ZEC than the strategy of Fig. 3. The second role of ZEC, comparable to GC, is, in this particular case, far more important to bring "Producer 1"'s ZEP_1 closer to the average market ZEP_M.

In a second run, both demand and supply come to equilibrium with ZEC trading. The economically sound emission-decrease objective is according to the calculation in Fig. 2. The planned emission decrease, the actual decrease and the contributions of both SS and DS are shown in Fig. 6. The decreasing level of demand is shown in Fig. 7.

In the model feedback loops from the decreasing demand to the supply market are missing. The

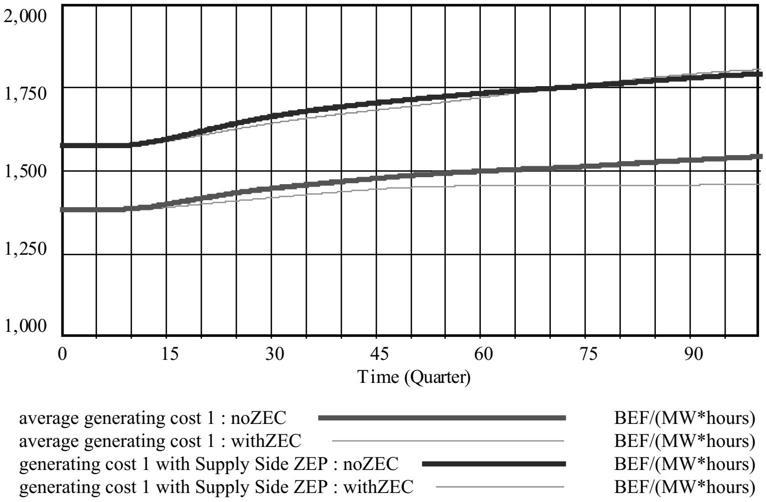

Fig. 5. The two lower curves show the average generating costs of "Producer 1", in case the substitution process is affected by ZEC-exchanges (thin line) or is not influenced (thick line). The two upper curves illustrate the corresponding total costs including the necessary acquisition of ZEC to bring the ZEP_1 in line with the whole SS.

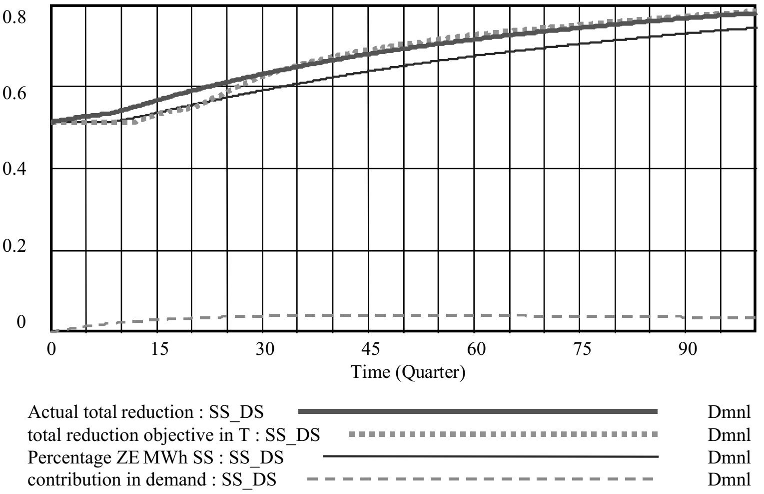

Fig. 6. The upper thick line represents the actual total emission-reductions expressed in ZEP [%] for the DS. This evolution is compared to the total reduction objective (point line) derived from forecasts of the SS and DS. The two lower curves represent the separate contribution of the SS (full line) and of the DS (dashed line) in the total emission reductions according to Eq. (3).

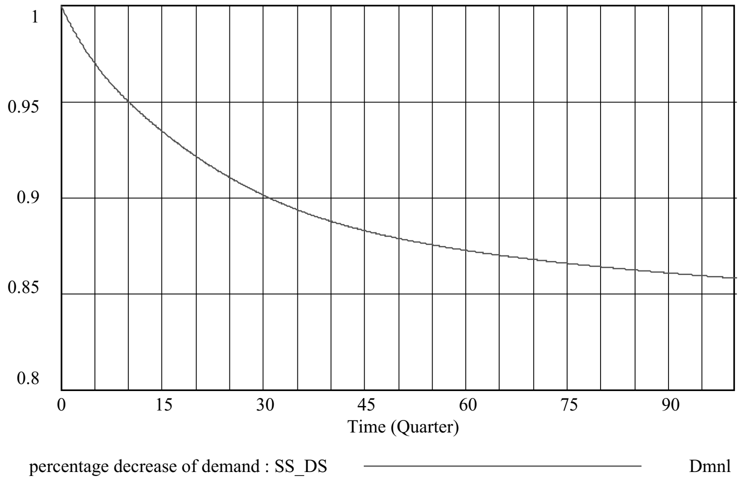

Fig. 7. The percentage level of demand [%] decrease while a cost arbitrage is made by the distributor between the market price of electricity and the marginal costs of RUE (rational use of energy) and of electricity economies (see Fig. 2).

assumption of constant market shares has been made, as it is thought to be sufficient to gain main insights into the model. An extension of the model to account for variable market shares is rather straightforward.

In a third and last run, "Producer 1" decides not to make usage of the ZEC-market, although he is substituting obsolete power according to the attractivity formula (8). It is shown in Fig. 8 that this producer is risking his complete elimination from the market, because an unfavourable attractivity gap appears according to Eq. (13). While demand is decreasing, available capacities are becoming available from other "cleaner" producers with more attractive ZEP-values.

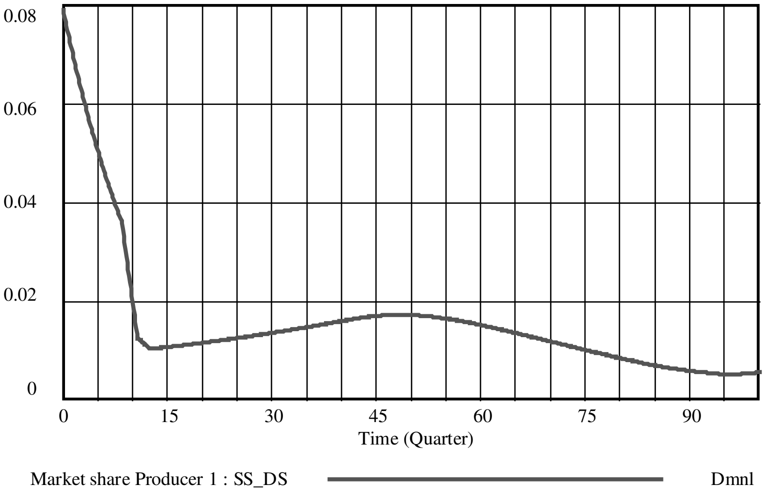

Fig. 8. Evolution of the market "share" of "Producer 1" [%] in case the latter is not buying any ZEC from the market to bring the ZEP_1 in line with the SS. The market share is dropping rapidly first. It recovers partially on a temporary basis as substitution policies improve somewhat the ZEP_1.

5. Final considerations

This paper shows how such seemingly very different mechanisms as taxes, trading emission permits, and GC can be merged in the case of CO_2-emission reductions. This has led us to propose an approach combining SS- and DS-management by introducing ZEC.

The incentives for making this proposal are observations on the complementary nature of the existing instruments, namely:

First, tax and permits have in common than they are based on the same optimisation mechanism of costs. Operator will act up to the level where marginal costs of reduction become equal to the tax, or to the carbon price, on the whole market.

Second, GC and CO_2-trading permits look like two different aspects of the same object.

Finally, the tax and the GC are both charged to the DS; the permits are exchanged on the SS.

A reconciliation of all these instruments clearly seems to be useful and a sensible thing to attempt. ZEC are used with a double purpose:

1. as an instrument amenable to trading between producers along the least-cost path (there is a strong similarity with the emission trading permits),
2. as a certification instrument to evidence the compliance with the regulator's objectives (there is a strong similarity with the GC).

By reflecting about this combined instrument, it appears that it is coherent and removes many of the difficulties sticking to the individual instruments:

The blindness and anonymous character of the tax is avoided by the transparency of the penalty charged to well-identified operators. The difficulties of trading permits are avoided in case ZEC are traded, as they reflect actual reduction efforts. No initial allocation needs to be defined, no “hot air” artefact is to be feared. While GC sales basically look like indirect subsidies to less competitive energy mixes, ZEC have the more efficient features of the emission permits.

Also it has appeared that the economic rationality and feasibility must remain central to all efforts made on both sides, supply and demand markets. Objectives shall be coming directly from the available reduction potential. They shall be implemented by the national or international regulators, like the European Union, on markets becoming increasingly international and competitive.

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