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Competition and environmental policies in an electricity sector*

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Abstract

In this paper, we study the impact of competition and environmental policy (feed-in tariffs vs. the EU ETS) on investment, CO2 emissions and welfare in an electricity sector. For this purpose, we consider different market structures (private monopoly, planner that maximizes the social welfare, dyopoly) and two types of consumers (consumers depending on weather and the other ones). The demand specification is innovative and takes into account an incompressible consumption.

Given the costs and demand functions we assume, competition increases CO2 emissions as it is highlighted in Mansur (2007). In duopoly, only the EU ETS seems to be the efficient policy in order to achieve the "3×20" aim: 20% of emissions reductions, 20% of production based on RES and 20% of energy efficiency. The EU ETS is effective to reduce CO2 emissions. The retained feed-in tariff policy is the most expensive for the "social welfare". Even if this policy seems to increase the "social welfare", feed-in tariffs increase the CSPE which is paid by consumers by higher electricity prices. It is also less effective in terms of emissions reduction.

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1 Introduction

Electricity production is responsible for 20% of total greenhouse gases (GHG) emissions in the world. Among GHG, CO2 is the most common and is mostly emitted through combustion of fossil fuel, industrial processes and deforestation[1]. Aware of the harmful effects of these emissions, the European Union (EU) has ratified the Kyoto Protocol. This protocol (1997) sets legally binding targets for industrialized countries, to stabilize CO2 concentration in the atmosphere. The EU-15 Member States are committed to reduce their GHG emissions in 2012 by 5.2% compared to 1990 levels. In April 2002, the EU agreed on different targets by country depending on economic circumstances and on accomplished progress since 1990. Since March 17^{th}, 2007, the EU-25 Member States confirmed the 17 propositions of the EU's package "Energy - Climate Change"[2] in order to strengthen the European policy on climate change. They have to reduce GHG emissions by 20% before 2020, or even by 30% if an international agreement is reached.

To achieve these objectives, the EU has implemented a marketplace for CO2 emission quotas: the European Union Greenhouse Gas Emission Trading Scheme (EU ETS). In January 2005 the EU ETS began to operate as the largest multi-country, multi-sector GHG emissions trading scheme worldwide, based on Directive 2003/87/EC. Another way to cap GHG emissions is the promotion of renewable energy sources (RES). So, the EU has decided on a binding target of 20% of renewable energy in the global European energy consumption, but national targets remain to be confirmed. Nevertheless political support to renewable energy technologies has a history of over 30 years within the EU. Policies promoting RSE are market-based instruments which can be distinguished between (direct or indirect) subsidies and tradable quotas. The European Commission survey (2005) established that the two common promotion measures were feed-in tariffs[3] and quota obligation systems with tradable green certificates. Thus the aim of these two different approaches, which are based either on price (i.e. feed-in tariffs) or on quantities (i.e. tradable quotas), is to internalise external effects and stimulate technical change.

Comparisons on renewable energy promotion policies often conclude that feed-in tariffs incur substantially excess cost in terms of public subsidies

[1]responsible for 20% of GHG.

[2]proposed on January 10^{th} and published on September 19^{th}.

[3]in seven out of the EU-15 Member States including France, which over the advantage to allow for differentiation between renewable technologies.

compared to tradable green quotas (cf. Menanteau, Finon and Lamy, 2003; Böhringer, Hoffman, Rutherford, 2006). This excess cost can be interpreted as the price tag that policy makers have to attach to reach other objectives[4] than the RES goal. Consequently, in theory the United-Kingdom scheme (quota and auction mechanisms) should be a lower cost mechanism than the German one (feed-in tariffs). But in practise, this is not the case as Butler and Neuhoff (2007) confirmed by focusing on one technology, onshore wind energy. Given this result and our interest in public policies implemented in France, we only study the EU ETS and feed-in tariffs in electricity sector. To our knowledge, the comparison of these two policies has not yet been studied. This may be justified by the fact that they do not pursue the same goal. Nevertheless, this comparison is relevant because, as noted above, feed-in tariffs and the EU ETS contribute to the reduction of CO2 emissions. We will therefore consider these two complementary mechanisms, and especially the impact of their implementation on investment, the volume of CO2 emissions, competition, prices and welfare.

We can use different articles, in order to answer at the following question: What are the impacts of these two mechanisms?

In the absence of competition and considering an annual load-duration curve, power is generated according to a chosen capacity mix, to meet demand at a minimal cost. Chaton (1997) determines optimal investment in thermal power plants in a two-period model. This model accounts explicitly for the nature of the electric demand through the load-duration curve and considers emission constraints. The extension proposed by Chaton and Doucet (2003) adds an additional period to her model and explicitly takes into account electricity trading.

Reinaud (2003) studies the impact of the EU ETS on electricity prices. She shows that in imperfect competition the electricity price does not totally include the CO2 emission price. Mansur (2007) finds that observed pollutions reductions can be attributed to firms exercising market power, based on evidence from the Pennsylvania, New Jersey, and Maryland Interconnection, a restructured wholesale electricity market opened to competition in 1999. So that it is important to take care of the industrial structure in addition to environmental constraints. Moreover, in a competitive situation, it would be advisable to integrate consumer's behaviour. Therefore, we propose a model that considers the behavior of producers who face heterogeneous demand.

[4] i.e. reduce additional market failures.

Madlener, Kumboglu and Ediger (2005) consider the impact of environmental constraints on investment decisions of firms that adopt a profit maximizing behavior on the competitive market. Kumboglu, Madlener and Demirel (2007) extend this model by considering learning curves for renewable energy technologies. Additionally, Pineau and Murto (2005) focus on investment decisions and competition in the long run. They question the competitive nature of European markets and compare competition and oligopoly maximizing profits. They also assume that supply is constrained by limited technologies (nuclear and hydropower), due to social-political considerations and the restricted availability of sites. It responds to a demand which is split between base and peak load periods for 80% vs. 20% of time. At last, Genc and Sen (2008) add a specification as competition takes place in wholesale markets where large user customers (e.g. industrials) pay market prices, while end-user customers pay fixed regulated prices. This modelling describes competition on electricity markets in Europe thus in France.

Consequently, the previously mentioned papers are either on environmental policies or on competition. Our goal is to look at the impact of these policies in a competitive environment after having shown the impact of competition on pollution emissions reductions. These impacts are analysed not only in terms of emissions, investments and consumption / production, but also in terms of consumers' surplus, firms' profits and welfare. We develop numerical models which focus on sequencing a one-stage decision and multi-period actions in order to model investments in generation capacities under deregulated environment. In Section 2, we expose the main modelling assumptions. In section 3, using French public data, we simulate the equilibriums in different market structures and under different environmental policies. The final section concludes and provides some elements of discussion.

2 The model

We consider several periods (years) denoted by $\theta = 1, \ldots, \Theta$. In order to take into account the seasonality of demand, year is composed of infraperiods, denoted by $t = 1, \ldots, T$.

2.1 Demand

The households' demand as well as public demand depend for most part on climate and consequently are seasonal. On the contrary, some industrials show a nearly flat demand. Thus, we consider two types of consumers[5]: consumers depending on weather[6], such as residential, commercial, public consumers (denoted by h) and the other ones (denoted by nh) who are independent on weather.

Consumer h. The inverse demand function of consumers h is defined by:

$$p_h\left(q_h\left(t,\theta\right)\right)=\overline{p}_h\left(t\right)-\alpha_h\frac{\overline{p}_h\left(t\right)}{\overline{q}_h\left(t,\theta\right)}q_h\left(t,\theta\right), \tag{1}$$

where $q_h\left(t,\theta\right)$ is the quantity demanded, α_h is a positive constant and $\overline{p}_h\left(t\right)$ is the price threshold that differs according infraperiods (t). At t, if the current price is greater than $\overline{p}_h\left(t\right)$, the demand equals zero. $\overline{q}_h$ can be considered as parameters for calibrating seasonal demand and is defined by the following equation:

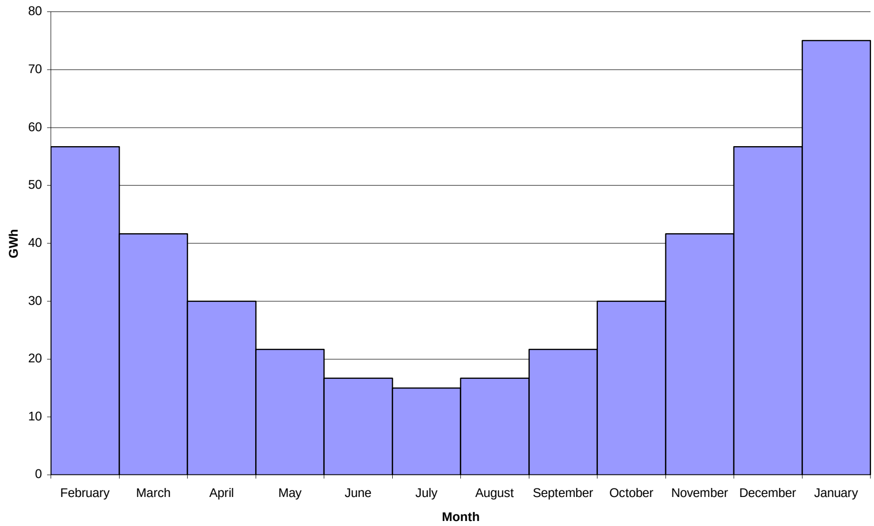
$$\begin{aligned}\overline{q}_h\left(t,\theta\right) \quad = \quad & \frac{4t^2\left(PKP\left(\theta\right)-BASE\left(\theta\right)\right)}{T^2} \\ & -\frac{4t\left(PKP\left(\theta\right)-BASE\left(\theta\right)\right)}{T}+PKP\left(\theta\right).\end{aligned} \tag{2}$$

We consider the period $[0,\ \theta']$ where the consumers h are not eligible or where regulated tariffs still exist. In this case, the incumbent is required to meet the demand of consumers who are not eligible as it is the case here or who want to be at the tariff. This demand is then only represented by the function $\overline{q}_h\left(t,\theta\right)$. Consequently, $\forall\theta<\theta'$, $p_h\left(q_h\left(t,\theta\right)\right)=tariff\left(\theta\right)$.

During the period when the tariffs still exist, the energy consumed by h for a year (i.e. 8760 hours) is approached by the sum upper integral of $\overline{q}_h\left(t,\theta\right)$. The same approximation, that can be represented for θ by the following figure, is also used for $\overline{q}_h\left(t,\theta\right)$.

[5] Consequently, we consider two markets (thus two prices).

[6] This is due to the large share of heating by electricity in France.



Demand of consumer h

Consumer nh. The inverse demand function for these consumers is flat and defined by the following equation:

$$p_{nh}\left(q_{nh}\left(t,\theta\right)\right)=\overline{p}_{nh}-\alpha_{nh}\frac{\overline{p}_{nh}}{\overline{q}_{nh}\left(\theta\right)}q_{nh}\left(t,\theta\right), \tag{3}$$

where α_{nh} positive constant. Unlike the case of consumers dependent on the weather, we assume that the price threshold, $\overline{p}_{nh}$, and the parameters, α_{nh} and $\overline{q}_{nh}\left(\theta\right)$, used to calibrate this demand are not seasonal.

The total **consumer surplus** is

$$\begin{aligned} CS &= \sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}(\overline{p}_{h}q_{h}\left(t,\theta\right)-\alpha_{h}\frac{\overline{p}_{h}}{2\overline{q}_{h}\left(t,\theta\right)}q_{h}^{2}\left(t,\theta\right) \\ &\quad +\overline{p}_{nh}q_{nh}\left(t,\theta\right)-\alpha_{nh}\frac{\overline{p}_{nh}}{2\overline{q}_{nh}\left(\theta\right)}q_{nh}^{2}\left(t,\theta\right))\left(1+r\right)^{1-\theta}, \end{aligned} \tag{4}$$

where r is the discount rate.

2.2 Supply

We study different market structures. So, we look at investment and production policies and their impact in terms of CO2 emissions and welfare in the following cases:

- Private Monopoly;
- Duopoly with an advantage for the incumbent and
- Planner that maximizes the social welfare.

For this, we develop several models in which we consider one or two producers. The two types of producers, denoted by a, are the incumbent ($a = I$) who is dominant and the others ones ($a = E$) who are alternative and aggregated smaller producers in our study.

Both actors have already invested in generation capacities, $PED\,(1, c, a) \in R^{C \times A}$, where C is the number of generation technologies c considered and $A = \{I, E\}$.

2.2.1 Private monopoly and duopoly

In the case of private monopoly and duopoly, the optimization problem to be solved initially for each actor a is thus:

Max [Net Present Value (NPV)] subject to the following constraints:

1. Total supply produced by each actor a = total demand expressed by both consumers;
2. For each actor a, installed available capacity $\geq$ supplied capacity;
3. (Plus some model specific constraints)[7].

The NPV is the present profit generated by production over the considered periods, net of fixed and variable exploitation costs, and net of investment costs. The variable costs include fuel (i.e. gas and oil, coal, uranium) costs. Production is sold by the incumbent at regulated tariffs to non eligible consumers or by any actor at market prices when consumers are eligible. Due to the evolution of regulation, we assume that consumers depending on weather are non eligible at first and become eligible in time. Nevertheless these two kinds of eligible consumers will not be supplied at the same market price on account of their different load profiles. Production supplies the demands expressed monthly by both kinds of consumers and cannot exceed the installed capacities which take into account lag of construction and decommissioning. Consequently, the objective function for the actor a is:

[7] These constraints mentioned are similar to Chaton (1997) and Chaton and Doucet (2003), without uncertainty and electricity trading, but with the addition of numerous periods.

$$
\begin{aligned}
\Pi_a &= \sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}\left(p_h(\theta,t)\,q_h(\theta,t,a)+p_{nh}(\theta,t)\,q_{nh}(\theta,t,a)\right)\frac{8760\,(1+r)^{1-\theta}}{T} \\
&\quad -\sum_{\theta=1}^{\Theta}\sum_{c=1}^{C}\left(\eta_c PED(\theta,c,a)+\iota_c PEI(\theta,c,a)\right)(1+r)^{1-\theta} \\
&\quad -\sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}\sum_{d=1}^{T}\sum_{c=1}^{C}\left(\omega_c+p_{c,a}r_c\right)PEF(\theta,t,d,c,a)\,\frac{8760\,(1+r)^{1-\theta}}{T} \qquad (5)
\end{aligned}
$$

where:

η_c (in euros per kilowatt of electricity or €/kWe) is the exploitation unit cost for the type of power station c;

ι_c (in €/kWe) is the investment unit cost for the station type c;

ω_c and r_c are non negative constants and r_c is the return of the station c;

$p_{c,a}$ is the price of the fuel used by the power station type c by producer a. Fuel prices are different for each producer according to the existence of long-term contracts (i.e. gas, nuclear);

$PEF(\theta,t,d,c,a)$ is the supplied electric power by the plant of type c by the generator a, used in the infraperiod t and in $(d-1)$ other infraperiods, d integer such as $1 \leq d \leq T$;

$PEI(\theta,c,a)$ is the new capacity purchased by the producer a for the station type c;

$PED(\theta,c,a)$ is the amount of the existing capacity of station type c of the producer a, in the period θ, which is defined by:

$$PED(\theta,c,a)=PED(\theta-1,c,a)-DEC(\theta,c,a)+PEI(\theta-\beta_c,c,a),$$

where β_c is the construction duration of station type c;

$DEC(\theta,c,a)$ the amount of decommissionning for station type c of the producer a in period θ;

$p_h(\theta,t)=p_h\left(\sum_a q_h(t,\theta,a)\right)$ is the inverse demand function of h. For $\theta=1,...,\theta'$ where $\theta'<T$, we assume that the consummers h are non eligible. So, if $\theta\leq\theta'$, $p_h(\theta,t)=tariff(\theta)$, only the incumbent meets the demand of h. Consequently, we have $q_h(\theta,t,I)=\overline{q}(t,\theta)$ and $q_h(\theta,t,E)=0$;

$p_{nh}(\theta,t)=p_{nh}\left(\sum_a q_{nh}(t,\theta,a)\right)$ is the inverse demand function of nh. The consumers nh are always eligible.

The constraints describing the power generation system are the following. First, the supply constraints state that the capacity allocated cannot exceed the purchased. Then the bounds on production due to the installed capacities and the availability rates must be verified as

$$\sum_{d=1}^{T} \frac{\sum_{t=1}^{T} PEF\,(\theta, t, d, c, a)}{d \times DISP(d, c)} \leq PED\,(\theta, c, a)\,,\ \forall \theta, c, a. \tag{6}$$

The avaibility factor of a power station, denoted by $DISP(d, c)$ depends on the technology c, the number of operating hours ($d\frac{8760}{T}$) and climatic conditions. Note that this factor includes the average rate of the maintenance and the rate unscheduled outage. The latter is random. Yet, here, one passes over the disturbance term. We assume that

$$DISP(d, c) = \alpha_d + \beta_d d \frac{8760}{T}.$$

The second constraint is inherent in the definition of $PEF\,(\theta, t, d, c, a)$, see Chaton (1997) for demonstration:

$$\sum_{t=1}^{T} PEF\,(\theta, t, d, c, a) - d.PEF\,(\theta, k, d, c, a) \geq 0,\ \forall \theta, k, d, c, a. \tag{7}$$

Third, for each producer a, the demand constraints state that the total supply of a in the infraperiod t in the period θ must be equal to the demand of the consumers depending on the weather and the demand of the other consumers expressed to a:

$$\sum_{d=1}^{T} \sum_{c=1}^{C} PEF\,(\theta, t, d, c, a) = q_h\,(\theta, t, a) + q_{nh}\,(\theta, t, a)\,,\ \forall \theta, t, a. \tag{8}$$

Algorithm. We use GAMS with MINOS to solve the optimization problems. In the case of duopoly we use an algorithm similar to that used by Pineau and Murto (2003). At the **first step**, $st = 0$, the incumbent maximizes his profit. We get a vector of control variables $V(I, 0)$ that maximizes the profit of the incumbent. This vector contains, among other things, $PEF^{st=0}\,(\theta, t, d, c, I)$; $PEI^{st=0}\,(\theta, c, I)$. Then, we can determine demand supplied by the incumbent (and prices) for each consumer, $q_h^{st=0}\,(\theta, t, I)$;

$q_{nh}^{st=0}(\theta,t,I)$; $p_h^{st=0}(q_h^{st=0}(t,\theta,I)+0)$ and $p_{nh}^{st=0}(q_{nh}^{st=0}(t,\theta,I)+0)$. The entrant takes $V(I,0)$ as given and maximizes his profit knowing $V(I,0)$. The result is $V(E,0)$. We obtain demand supplied by the entrant and market prices for each consumer, $q_h^{st=0}(\theta,t,E)$; $q_{nh}^{st=0}(\theta,t,E)$; $p_h^{st=0}(q_h^{st=0}(t,\theta,I)+q_h^{st=0}(t,\theta,E))$ and $p_{nh}^{st=0}(q_{nh}^{st=0}(t,\theta,I)+q_{nh}^{st=0}(t,\theta,E))$.

At the st^{th} **stage**, the incumbent takes as given $V(E,st-1)$ and maximizes its profit. We obtain the optimal control variables $V(I,st)$ and associated prices. Then, the entrant maximizes its profit in light of this information.

The **stopping condition** loop is the following: The sum of the squared differences between control variables at the stage $st+1$ and the stage st must be equal to zero. Consequently, we have: $\forall\theta,t,d,c,a$ and $st>1$

$$\left(PEF^{st}(\theta,t,d,c,a)-PEF^{st-1}(\theta,t,d,c,a)\right)^2 + \left(PEI^{st}(\theta,c,a)-PEI^{st-1}(\theta,c,a)\right)^2=0.$$

This type of algorithm gives an advantage to the first player. We select this algorithm and choose that the incumbent plays first. The incumbent may have this advantage compared to the entrant, advantage that may reflect a better knowledge of the firm by the market.

2.2.2 Social Welfare Maximisation

We assume that a regulator maximizes social welfare (Π_I+CS) where Π_I is defined by (5) and CS by (4).The constraints are similar to the constraints of the two previous market structures (see (6)-(8)). We add the participation constraint $\Pi_I\geq 0$.

2.3 Environmental policies

These models are modified as followed according to environmental policy.

2.3.1 The EU ETS

The EU ETS restricts emissions of European electricity actors. The constraints (i.e. allocations of quotas) are established at the national level by National Allocation Plans (NAPs) for the electricity sector. In France, the NAP sets a constraint of 35.92 million tons of CO2 per year (MtCO2/y) for the first phase (2005-2007). It strengthens it for the second phase (2008-2012) with a decrease to 25.592 MtCO2/y. On January 23^{rd} 2008, A. Piebalgs, the

European Commissioner of energy, announced his project[8] concerning emissions constraints for the third phase running from 2013 to 2020[9]. The NAPs transpose these sectorial constraints into installation-level allocations. The methods[10] used to determine installation-level allocations of quota, include baseline changes, commissioning and rationalization rules. In France, allocations are based on "grandfathering": quotas are allocated freely on the basis of historical emissions. But new power stations, except for extensions of plants, are allocated quotas according the Best Available Technologies (BAT) using the less pollutant fuel, natural gas.

Firms receive quotas and can buy additional permits or sell permits if they have some in excess on the EU ETS. But the EU ETS is an European market which concerns some industrial sectors as well as energy sectors, and caps the emissions of these sectors. Furthermore the historical prices of emission permits do not seem to ease forecasts of prices in the future. At the end of the first phase, the prices of permits have fallen to nearly zero because many actors on this EU ETS realized that they had been allocated excess permits and banking[11] was not allowed. As a result, we consider that when producers make their investment decisions they do not take into account the possibility to exchange quotas. When we will have more information[12] on the functioning of the CO2 trading market, we will take into account this market with exogenous and random prices of CO2 and this will be a natural extension of the model. For the moment, we consider only the constraints imposed by the NAPs. So, we assume that the French electricity sector thus electricity firms have to face an exogenous cap, which is a global (modulo exchanges, which are included in this cap) constraint for this sector. We consider a cap of 23 MtCO2/y (resp. 14.4 MtCO2/y) from February 2005 to January 2008 (NAP 1) for the incumbent (resp. entrant). Then we take into account the evolution of an exogenous cap[13] according to the formula for

[8] still debated. Nevertheless quotas will not be anymore allocated freely, but on an auctions basis.

[9] These constraints have to take into account the goals already fixed by the European Commission: -20% of CO2 emissions, +20% for energy efficiency and a share of 20% of renewable energy in the energy consumption by 2020.

[10] The EU ETS allows two means to allocate free quotas : "Grandfathering" and Best Available Technologies (BAT). In BAT, the emission factor is fixed according the fuel or the less pollutant fuel (i.e. natural gas). See C. Levy (2005) for a good description of the EU ETS.

[11] The banking is the possibility given to the actors on the EU ETS to use permits given in a phase in the following one.

[12] Firms have been over-allocated during the NAP 1 phase.

[13] as in Gilbert, Reece and Phylipsen (2006): "The European Commission states that the objective of the scheme [EU ETS] is "to promote reductions of greenhouse gas emissions

the second phase (NAP 2). Both generators are submitted to an additionnal constraint which represents the policy with quotas.

During each period (year) during the NAP 2 (for 2008/02 to 2012/01) and after[14], emissions must be lower than a threshold of quotas:

$$\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d} \leqslant S(\theta,a),\ \forall\theta,a \tag{9}$$

where φ_c is the emissions factor of station c and $S(\theta)$ (in CO2 tons, tCO2) are emissions thresholds during the period θ and are constants, defined by (11). In reality, if the producer has not exhausted its quota, it may be postponed and thus increase the quotas will be allocated in the following year. Consequently, (9) must be replaced by

$$\begin{aligned}\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d} &\leqslant S(\theta,a)+S(\theta-1,a)\\ &-\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d},\ \forall\theta,a\end{aligned} \tag{10}$$

$$\begin{aligned}S(\theta+1,a) &= \sum_{d=1}^{T}\sum_{c=1}^{C}\left(\rho.g\left(1-0.025\right)\right)\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d}\\ &+\sum_{c=1}^{C} h_c\Phi\left(\theta,c\right)PEI\left(\theta,t-\beta_c,a\right),\ \forall\theta,a\end{aligned} \tag{11}$$

where ρ and g are two positive constants, a rate defined by the NAP and the GDP rate; $\Phi\left(\theta,c\right)$ is the emissions factor of new station c built after the first period; h_c is the functioning hours of each new station c defined in the NAP.

For the second phase, we do not take into account the formula described above where the producers receives quotas according to its amount of investment and also its production planning for the following reason. The producer

in a cost-effective and economically efficient manner." The central purpose of the scheme is therefore to stimulate greenhouse gas emissions reductions in a way that provides more flexibility in meeting emissions reduction targets.

For the purposes of this study, the concept of an "ideal NAP" refers to a cap, and surrounding decisions, that put a Member State on track to meeting its Kyoto greenhouse gas emissions target, whilst taking into account the criteria from the Emissions Trading Directive and associated Commission Guidelines."

[14] For 2012/02 to 2021/01. We extend the period because the NAP 3 is not yet defined.

may have an interest to make a lot of emissions in the early years (saturates (9)) to increase its quotas for the next years. In order to not incite the entrant to pollute more, we adapt the constraint to only take into account investment (PEI). We replace (11) by the following equations.

$$S(\theta+1,a) = \alpha S(\theta,a) + \sum_{c=1}^{C} h_c \Phi\left(\theta, CCGT\right) PEI\left(\theta, t-\beta_c, a\right) \frac{8760}{T}, \ \forall \theta, a \tag{12}$$

For the second phase, the amount of allocated quota in following period (year) $\theta+1$, is equal to a percentage of the quota amount of the previous year, plus a percentage of quota allocated on the investment basis. The latter percentage is constrained, thus we have:

$$\sum_{a}\sum_{c=1}^{C} h_c \Phi\left(\theta, CCGT\right) PEI\left(\theta, t-\beta_c, a\right) \frac{8760}{T} \ \leq \overline{S}(\theta), \quad \forall \theta. \tag{13}$$

Thus, this inequality imposes a superior bound on the investments of the polluting technologies.

Remark: If we take into account the possibility to exchange quotas, (10) can be rewritten

$$\begin{aligned}\sum_{c=1}^{C}\sum_{d=1}^{T}\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d} \quad &\leqslant \quad \left(S(\theta,a)+S(\theta-1,a)\right)\frac{T}{8760} \\ &\quad -\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF\left(\theta,t,d,c,a\right)}{d} \\ &\quad +\sum_{t=1}^{T} X^{+}\left(\theta,t,a\right)-\sum_{t=1}^{T} X^{-}\left(\theta,t,a\right), \ \forall \theta, a.\end{aligned}$$

where $X^{+}\left(\theta,t,a\right)$ (respectively $X^{-}\left(\theta,t,a\right)$) is the purchase (resp. sale) of quotas by the actor a in the infraperiod t of the period θ. The objective function is

$$\Pi_a^{CO2} = \Pi_a + \sum_{\theta=1}^{\Theta}\sum_{t=1}^{T} P_{CO2}\left(\theta,t\right)\left(X^{-}\left(\theta,t,a\right)+X^{+}\left(\theta,t,a\right)\right)\frac{8760\left(1+r\right)^{1-\theta}}{T}$$

where Π_a is defined by (5) and $P_{CO2}\left(\theta,t\right)$ is the CO2 price in the infraperiod t of the period θ.

2.3.2 Feed-in tariffs

In France, the incumbent is required to buy the electricity produced using renewable sources. Then it sells this quantity of electricity to the market. He is reimbursed by the difference between feed-in tariffs and the spot market price according renewable source via the Contribution to the Electricity Public Service (CSPE[15]). The other actors face a twofold option: either they sell their electricity to the incumbent at feed-in tariffs or to consumers at market price .

Remark: Feed-in tariffs can be viewed as direct subsidies which lower the exploitation unit cost of green-power stations.

The basic model is modified as follows. The objective function of the entrant E becomes:

$$\begin{aligned}&\left(\sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}\left(p_{nh}\left(\theta,t\right)q_{nh}\left(\theta,t,E\right)+PGS\left(t\right).QGS\left(\theta,t,E\right)+PGW(t).QGW\left(\theta,t,E\right)\right)\right.\\&+\sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}p_{h}\left(\theta,t\right)q_{h}\left(\theta,t,E\right)\\&\left.-\sum_{\theta=1}^{\Theta}\sum_{t=1}^{T}\sum_{d=1}^{T}\sum_{c=1}^{C}\left(\omega_{c}+p_{c,E}r_{c}\right)PEF\left(\theta,t,d,c,E\right)\right)\frac{8760(1+r)^{1-\theta}}{T}\\&-\sum_{\theta=1}^{\Theta}\sum_{c=1}^{C}\left(\eta_{c}PED\left(\theta,c,E\right)+\iota_{c}PEI\left(\theta,c,E\right)\right)\left(1+r\right)^{1-\theta}\end{aligned}$$

where $QGS(.)$ and $QGW(.)$ (in kWe) are the quantities produced by solar PV and windmills to be sold to the incumbent at feed-in tariffs $PGS\left(t\right)$ and $PGW(t)$.

The incumbent is obliged to buy $QGS(.)$ and $QGW(.)$, produced by the entrant. These quantities are not variables of decision for the incumbent. Following, the objective function is similar to the one corresponding to the program without environmental policy. We suppose that the quantities produced by the entrant's solar PV and windmills sold to the incumbent at feed-in-tariffs and satisfy part of the demand of climate independent customers. Consequently, the inverse demand function of these customers (i.e. equation (3)) can be rewritten as follows:

$$p_{nh}\left(q_{nh}\left(t,\theta\right)\right)=\overline{p}_{nh}-\alpha_{nh}\frac{\overline{p}_{nh}}{\overline{q}_{nh}\left(\theta\right)}\left[q_{nh}\left(t,\theta\right)-QGS(t,\theta,E)-QGW(t,\theta,E)\right].$$

[15] Contribution au Service Public de l'Electricité.

3 Simulations

3.1 Data

The model is applied to public data on the French market (cf. DGEMP, 2003, 2006, 2007). We use GAMS with MINOS to solve these five optimization problems, so that we can compare them, over 15 years (from February[16] 2006 to January 2021). By hypothesis, the discount rate equals 5%.

3.1.1 Demand

In France, professional consumers became eligible in July 2004 and the residential consumers became eligible in July 2007. Since then they still have the choice to be supplied by the incumbent at a regulated tariff approved by the government[17] after notice of the regulator, CRE[18]. This regulated tariff should exist until July 1^{st} 2010, but could be removed at any time.

In broad outline, we assume that consumers depending on weather are non eligible during the first two years, from February 2006 to March 2008. They pay a regulated tariff established by the government at 0.1029 euros per kilowatt hour (€/kWh) the first year and 0.1203 €/kWh the second year. Then they become eligible such as the other ones who are independant to weather[19]. So they can be supplied either by the incumbent or by the others operators.

Demands of consumers are described below. Base and peak loads of consumers h when they are not eligible are equal to: $BASE\,(1) = 23$ gigawatt hours (GWh), $BASE\,(2) = 23.4$ GWh, $PKP\,(1) = 37.4$ GWh and $PKP\,(2) = 36.1$ GWh. For the following years ($\theta \geq 3$), when consumers h are eligible, base and peak loads do not increase. Load profiles of consumers nh are characterized by $\overline{q}_{nh}\,(1) = 9.8$ GWh, $\overline{q}_{nh}\,(2) = 9.9$ GWh and increase[20] by 2% for the following years. To calibrate demands, we assume

[16] In order to switch well real demands and peak loads, year begins in February.

[17] more precisely by the ministry in charge of economy, finance and industry (Ministère de l'Economie, des Finances et de l'Industrie), then after June 2007 in charge of economy, finance and employment (Ministère de l'Economie, des Finances et de l'Emploi).

[18] Commission de Régulation de l'Energie.

[19] We don't take into account the fact that eligible professional customers can ask their supplier (incumbent or entrants) to benefit from the regulated tariff, TaRTAM (tarif réglementé transitoire d'ajustement du marché), that is implemented on January 5th 2007. This regulated tariff includes a penalty, but is not volatile as market prices, and is available only for a determined and transitory period.

[20] After the demand peak of December 17th 2007, at 7 pm, D. Maillard who is the head of RTE (Réseau de Transport d'Electricité) highlighted that the demand peak increases the most. RTE expects demand peaks of 95 000 MW in 2010 and 103 000 MW in 2020.

$\alpha_h = 1.8$ and $\alpha_{nh} = 1$. Price thresholds for both types of consumers are defined in the table. We suppose that the prices thresholds are constant for the weather independent customer. On the contrary, the weather dependent customers are ready to pay expensive bills during winter.

Months	$\overline{p}_h$	$\overline{p}_{nh}$
01 (February)	1.9	0.8
02 (March)	1.2	0.8
03 (April)	1.2	0.8
04 (May)	1.1	0.8
05 (June)	1.1	0.8
06 (July)	1.1	0.8
07 (August)	1.1	0.8
08 (September)	1.3	0.8
09 (October)	1.7	0.8
10 (November)	1.9	0.8
11 (December)	1.9	0.8
12 (January)	1.9	0.8

Table 1. Price thresholds for climate-dependent and climate-independent consumers.

3.1.2 Supply

Technologies. We consider 10 technologies ($card(C) = 10$). These technologies include Nuclear Power Plants (NPPs), large hydroelectric plants (HCHPs) and small hydroelectric plants (SCHPs), two technologies of coal-fired power plants which differ on costs and emissions (pulverized coal, COAL1, and flue gas desulphurization process, COAL2), combined cycle gas turbines (CCGTs), wind turbines (WIND), solar PV (SOLAR), fuel power plants (FUEL) and gas turbines (GTs). We do not consider biomass because investment costs are dependant on the size of plants, which doesn't allow to estimate unified costs per kWh. Biomass is also essentially a decentralized means of production in France[21]. Thus it is taken into account in the evolution of the climate dependent demand. Moreover, we do not take into account technical progress. For example, we do not integrate the most recent coal based generation technologies such as those carbon capture and storage (CCS) which is not yet profitable. There is a scientific debate on

[21] That could change after the impulsion given by the Grenelle de l'environnement, a set of political meetings held in France in October 2007, aiming to make long-term environmental and sustainable development.

this question, and in May 2007 a panel of experts on CCS told US legislators that the technology is ready for large-scale demonstration projects to speed its development, making it commercially viable in the next decade.

Construction lags differ according technologies (cf. Table 2 below).

Initial capacities of actors. The assumed initial capacities of the incumbent are presented in the table below. The actor $E's$ aggregated capacities located in France include those of Suez (with two subsidiaries, CNR[22] and SHEM[23]), Endesa France and Gaz de France.

Generating technology (MW)	Incumbent I	Entrant E	Construction duration β_c
NPP	62840	0	7
HCHP	18800	2.937	4
SCHP	1800	0.773	2
COAL1	7042	2.477	5
COAL2	993	0	5
CCGT	0	0	4
WIND	228	0	1
SOLAR	0	0	1
FUEL	7521	0	2
GT	203	2.39	2

Table 2. Initial capacities of both actors and construction lags according technologies.

We assume that there is no possibility to invest in HCHP and that total investment in SCHP is bounded up to 2 GW. We do not detail here the investment and exploitation costs, which can be found in DGEMP (2003).

Remark: Hydropower is not considered as an avoided cost.

Availability functions. These functions noted $DISP(d, c)$, and defined in 2.2, depend on technology type c and the number of operating hours (see Table in appendix A for the value of parameters). We assume that solar PV stations do not produce during the following months: March, October, November, December, January and February.

Fuel costs. We consider the lowest scenario given by DGEMP (2003). Hence, in February 2006, we have the following values for the price of the

[22] Compagnie Nationale du Rhône.

[23] Société Hydroélectrique du Midi.

various fuels: 3.3 \$/MBtu[24] for gas; 177.3 euros per cubic meter (€/m^3) for oil; 30\$/ton for coal and 4.4 €/MWh for uranium. The increase of oil (respectively gas) price is equal to 5% (respectively 3%) per year. The other prices are assumed constant[25].

3.2 Environmental policies

Emissions. Below, for each scenario (without and with each environmental policy) we determine CO2 emissions due to production by considering the DGEMP emission factors, given for new plants built in 2007 and in 2015 (which emit less).

The EU ETS. We assume that, without investment in polluting technology the quota reduction is 20% and that the additional quotas granted as a result of investment in polluting technologies can not exceed 3.005 Gt of CO_2 emission. So in the equation (9) $\alpha = 0.8$ and in the equation (13) $\overline{S}(\theta) = 3.005\ \ e6$[26]. Our calibrations assume that $\Phi(\theta, CCGT) = 365$ gCO2/kWh and consider 5 polluting technologies: combined cycle gas trurbines (CCGT), two technologies of coal fire plants (COAL1, COAL2), gas turbines (GT) and fuel power plants (FUEL) where

$$h_c = \begin{cases} 12 \text{ if } c \in \{CCGT; COAL1; COAL2\}, \\ 2 \text{ if } c = GT, \\ 1 \text{ if } c = FUEL. \end{cases}$$

Feed-in tariffs. They are implemented in France. According to the JO[27] order of July 10^{th} 2006, feed-in tariffs for solar PV are equal to 0.30 €/kWh during 15 years. Feed-in tariffs for windmills are equal to 0.82 €/kWh during 10 years and, during 5 years more, to:

- 0.028 €/kWh if windmills produce during 3650 hours and more;
- 0.068 €/kWh if windmills produce between 2190 and 3650 hours;

[24] Dollars per one million British Thermal Unit.

[25] This assumption for coal and uranium is justified by the existence of long term contracts and the possibility of storage.

[26] We make an analysis of sensitivity compared to $\overline{S}(\theta)$ of profits, social surplus, the amount of CO2 emissions and investment was made. The results are included in Appendix.
According to the values of $\overline{S}(\theta)$, it is possible that the program is unfeasible. The introduction of a market of quotas would end this infeasibility. But as noted above, given the difficulty of predicting the future price in this market, we do not see.

[27] Journal Officiel.

- 0.082 €/kWh if windmills produce during 2190 hours and less.

3.3 Results

The impacts of competition and environmental policies are analyzed according to the cost beared by society, to the CO2 emissions reductions and to the improvement of competition. The table 3 summarizes the results for the five following cases.

In order to highlight the impacts of competition, we put in perspectives the results obtained for the duopoly with the ones for the private monopoly as well as the ones for maximizing the total welfare[28]. The impacts of environmental policy (the EU ETS vs feed-in tariffs) are then compared to the case of the duopoly which is not constrained by any environmental policy.

Total over 2006/02 – 2021/01	Maximisation Total Welfare - monopoly	Monopoly	Duopoly	Duopoly constrained by the EU ETS	Duopoly benefiting from Feed-in tariffs
Consumer Surplus (b€)	2,822	2,360	2,903	2,904	3,054
Profit - I (b€)	1,405	1,580	844	879	793
Profit - E (b€)			378	342	1,223
Welfare (b€)	4,227	3,940	4,125	4,125	5,070
CO_2 emissions (Gt)	49.36	21.31	880.62	11.48	566.69
Incumbent	49.36		2.58	10.74	24.42
Entrant			878.05	0.75	542.28
Investment (GW)					
NPP_E				2.85	
SCHP_E			2.00	2.00	2.00
CCGT_E			5.28	0.03	3.29
GT_E			15.72		7.85
COAL1_E			11.64		6.50
COAL2_E					
FUEL_E			2.38		
SOLAR_E					18.83
WIND_E			7.65	44.14	39.53
Consumption (GW)	5,231,213	3,998,050	5,476,993	5,507,227	5,736,489
NPP	59.09%	46.91%	58.24%	37.20%	53.74%
HCHP and SCHP	38.63%	52.31%	12.51%	38.27%	12.18%
CCGT			5.29%	0.03%	3.37%
GT			1.87%	0.23%	4.76%
COAL1 and COAL2	2.10%	3.21%	18.00%		9.00%
FUEL			0.26%		
SOLAR					7.37%
WIND	0.12%	0.69%	3.83%	24.27%	9.59%

Table 3. Impacts according to cases (where b€ is billions €).

[28]By doing that, we assume that firms act and invest as a monopoly constrained to maximize the total welfare, i.e. the monopoly profit and the consumer surplus.

Given our assumptions, whatever the market structure and environmental policies considered, the incumbent does not invest over the period 2006-2021. The entrant's investment is diversified and varies according to environmental policies. The entrant does not invest anymore in pulverized coal station but still saturates the hydroelectric capacity constraint. (See Appendix B for the investment planning.)

When no environmental policy is imposed, the entrant invests primarily in gas-fired power plants (21 GW) but also in coal-fired plants (11.64 GW) and windmills (7.65 GW) and marginally in fuel-fired plants (2.38 GW). Means invested in order to supply peak-load demand approximate 41% (i.e. 18.1 GW) of the total investment. All the investment is realized at the first year 2006-2007. In absence of environmental policy, the share of investment in RES is about quarter (22%). The national production runs with 75% of non pollutant plants (16% without taking into account the NPPs generation), compared to 99.9% (53% respectively) in the case of a private monopoly, 989% (39% resp.) in the case of maximizing the total welfare. We wonder about the percentage of supply served by NPPs. We can note that NPPs run more when non independent consumers are supplied at the regulated tariff during the first two years and not at the market price. We also have to take into account the fact that we have not modelized imports / exports.

Finally we can notice that CO_2 emissions are higher in the case of duopoly without any environmental policy compared to the situation of maximizing welfare with monopoly or to the situation of a private monopoly. Explanations are as follows. Demand increases following the entry of a competitor. In addition, a percentage of consumers has changed in order to be supplied by the entrant instead of the incumbent. A part of the demand that was previously satisfied with the operation of hydropower and nuclear power plants, is now satisfied by the fossil-fueled power plants (which are peak-load means) of the entrant. Note that the CO_2 emissions are higher in the case of maximizing welfare with monopoly than in the case of a private monopoly due to the lower demand (involving lower welfare).

The EU ETS as environmental policy is a means to rationalize the choice of investment in non polluting plants. Compared to the situation of duopoly without environmental policy, the entrant invests in NPPs (2.85 GW), more in windmills (44.14 GW instead of 7.65 GW). Obviously, the duopoly pollutes less if it is constrained by the EU ETS than in the situation where it is not constrained: 11.48 CO_2 Gt, instead of 880.62 CO_2 Gt[29]. Demand is supplied

[29] Note that with EU ETS, the consumptions (prices) are similar to the consumptions corresponding to the duopoly case without constraint. The consumer surplus is the same

by 94% of non pollutant plants (and 57% without taking into account the NPPs generation) in the case of a duopoly constrained by the EU ETS. This is more than the percentage obtained when the duopoly benefits from feed-in tariffs: 83% (29% resp.).

Note that the entrant's national investment, in terms of percentage in RES, is higher in the case of the duopoly constrained by the EU ETS than in the case of the duopoly benefiting from feed-in tariffs: 99.9% in non pollutant plants, i.e. accounting NPPs, (and 94% in RES) in the case of the duopoly constrained by the EU ETS vs. 77% in RES in the case of the duopoly benefiting from feed-in tariffs. In the latter case, the entrant invests greatly in solar PV plants (18.83 GW). Because of the assumption of low availability of solar energy during winter and fall, the entrant is obliged to invest in other technologies to meet the annual demand[30]. As the entrant delays[31] its investment in conventional plants (half of the 0.03 GW of GTs) in the duopoly constrained by the EU ETS, it delays also its investment in decentralized plants (45% of windmills and 8% of PV plants, in addition to 47% of coal-fired plants) in the duopoly benefiting from feed-in tariffs. In this latter case, the entrant all together extends its RES park and invests in peakload means of production.

It is interesting to note that feed-in tariffs are strong incentives for the entrant to invest in solar plants (18.83 GW) and windmills (39.53 GW). The total welfare is higher than if the environmental policy is the EU ETS. The profit of the entrant who benefit from feed-in tariffs increases, such as demand and consumer surplus. Note that this surplus does not take account of funding associated with feed-in tariffs. Thus, given the requirement for the incumbent to buy electricity generated by wind and solar plants, this renewable energy quantity has been removed from the objective function of the incumbent and from the demand of consumers independent of weather (see equations 8 and 12). The incumbent must be compensated via the CSPE (see the footnote 13). This difference would be compensated by consumers and would diminish their surplus. Therefore, the feed-in tariff policy is only profitable to the entrant. The entrant does not invest in NPPs which is not a susidizied means. Finally this duopoly which benefits from feed-in tariffs pollutes more than when it is constrained by the EU ETS: 566.69 CO_2 Gt, rather than 11.48 CO_2 Gt. The increase in CO_2 emissions compared to the EU ETS case is, on the one hand, explained by the growth in demand, and, on the other hand, by the use of polluting technologies when solar and wind

and the total social welfare is almost the same.

[30] For more details on the production the reader can refer to Appendix B.

[31] after the first two years (2006-2007 and 2007-2008).

power plants are unavailable.

Given our assumptions, in the case of private monopoly, the consumption is clearly lower than the consumption in the duopoly cases and in the case where planer maximizes social welfare. If we retain as criterion the total social surplus and the amount of CO_2 emissions, a planer who maximizes the social welfare with a monopoly of production seems here to be the best solution. But, the consumer prefer his situation in the case of duopoly to his one when the social planer maximizes the welfare, and finally to monopoly. If the objectives are the competition with the least CO_2 emission, it is preferable to choose the duopoly with the quota policy that we selected. So, feed-in tariffs are only profitable to the entrant.

4 Conclusion

Our model allows us to analyze the consequences of environmental policies on the electricity market. Our framework is that of the pluriannual programmation of investments in France (Programmation pluriannuelle des investissements de production d'électricité 2005-2015, PPI by DGEMP), without imports nor exports of electricity and CO_2 permits. We analyze decisions of an incumbent and its competitors who have to supply two kinds of demands[32], one depending on weather and a climate independent one. We respectively test the impact of feed-in-tariffs and quotas obligation systems on decisions of this incumbent and its competitors, aggregated and denominated alternative producers.

Given our assumptions, only the EU ETS seems to be the efficient policy in order to achieve the 3×20 aim: 20% of emissions reductions, 20% of production based on RES and 20% of energy efficiency. The EU ETS is effective about reductions of CO_2 emissions: the duopoly emits nearly 99% of CO_2 less when it is constrained by the EU ETS than when it is unconstrained. Indeed, the feed-in tariff policy incites the entrant to invest 18.83 GW in solar PV stations. Because of the low availability rate of the solar PV plants, the entrant combines this technology with gas turbines that increase the CO_2 emissions. The retained feed-in tariff policy is the most expensive for the "social welfare". Even if this policy seems to increase the "social welfare", feed-in tariffs increase the CSPE which is paid by consumers by higher electricity prices. It is also less effective in terms of emissions reduction. In that we are in line with theoretical literature on feed in tariffs and quotas obligation system (Menanteau, Finon Lamy, 2003; Böhringer, Hoffman,

[32] without distinguishing extreme peak-load demand and peak-load demand.

Rutherford, 2006).

Furthermore, constrained by the EU ETS, the duopoly produce in percentage 46 points more than the duopoly without any environmental policy with RES (and 25 points more if we take into account the NPPs generation). With feed-in tariff policy, the duopoly production with RES in percentage is 13 points higher (resp. 8 points with NPPs included) than the duopoly without any environmental policy.

As our goal is to focus on a comparison of environmental policy efficiency we subscribe to a set of assumptions that could be adapted to broaden the issues under study. Therefore, the model can be extended in several directions to illustrate other topical stakes on the electricity market. Measures of released capacities (i.e. Virtual Power Plants) can be introduced by the regulator[33] in order to allow the entrant to penetrate the market without capacity.

Finally the EU ETS is the environmental policy which restrains demand. In order to reach 20% of energy efficiency, we should also take into account the fact that the RES are also a means of decentralized production, which lowers demand. At last, the part of consumers who decide to be supplied by the entrant can be uncertain: the incumbent benefits from a reputation built in the long run. According to this degree of competition based on this share of consumers who prefer such or such generator, the comparison of environmental policy efficiency could vary.

5 References

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6 Appendix A: Availability factor

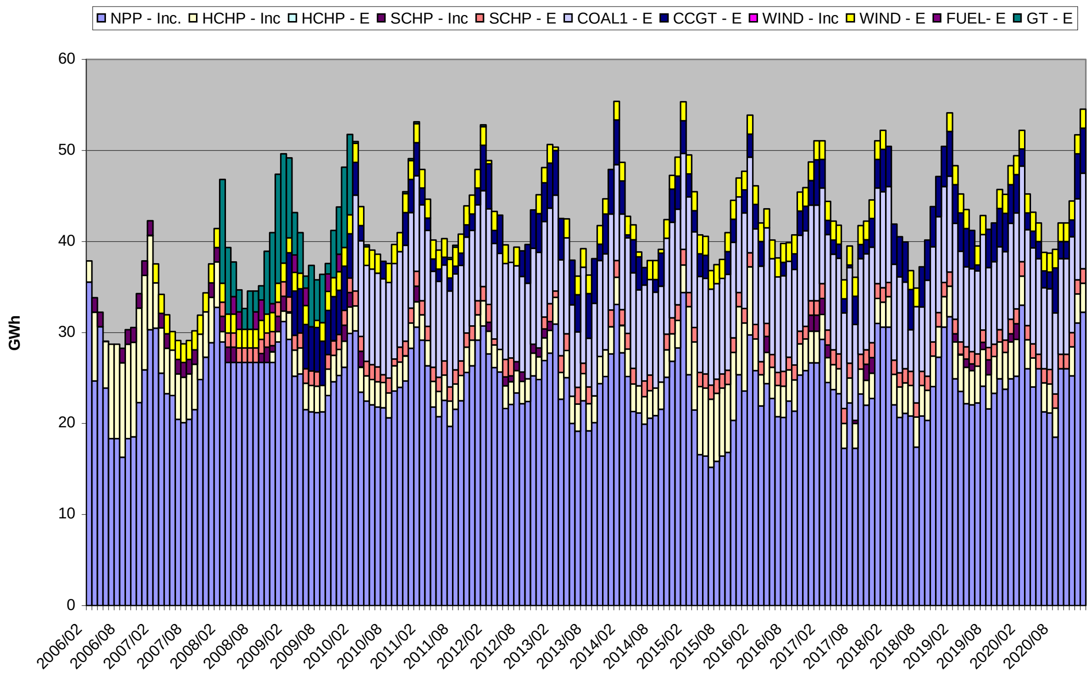
Number of operating hours $d \frac{8760}{12}$	≤ 1000 hours		]1000;4000] hours		> 4000 hours	
Generating technology	α_d	β_d	α_d	β_d	α_d	β_d
NPP	0.984460158	$-9.36582\ 10^{-6}$	0.984460158	$-9.36582\ 10^{-6}$	0.984460158	$-9.36582\ 10^{-6}$
HCHP	0.9	0	0.9	0	0.9	0
SCHP	0.97	0	0.97	0	1.103154545	$-3.67424\ 10^{-5}$
COAL1	0.944941667	$-7.275\ 10^{-6}$	0.944941667	$-7.275\ 10^{-6}$	0.935112094	$-3.66586\ 10^{-6}$
COAL2	0.944941667	$-7.275\ 10^{-6}$	0.944941667	$-7.275\ 10^{-6}$	0.935112094	$-3.66586\ 10^{-6}$
CCGT	0.956367545	$-4.1517\ 10^{-6}$	0.956367545	$-4.1517\ 10^{-6}$	0.956367545	$-4.1517\ 10^{-6}$
WIND	0.27	0	0.27	0	0.27	0
SOLAR	0.34	0	0.34	0	0.34	0
FUEL	0.97	0	0.973099985	$-8.83475\ 10^{-6}$	0.973099985	$-8.83475\ 10^{-6}$
GT	0.97	0	0.973099985	$-8.83475\ 10^{-6}$	0.973099985	$-8.83475\ 10^{-6}$

Availability factor of different technologies according to number of operating hours.

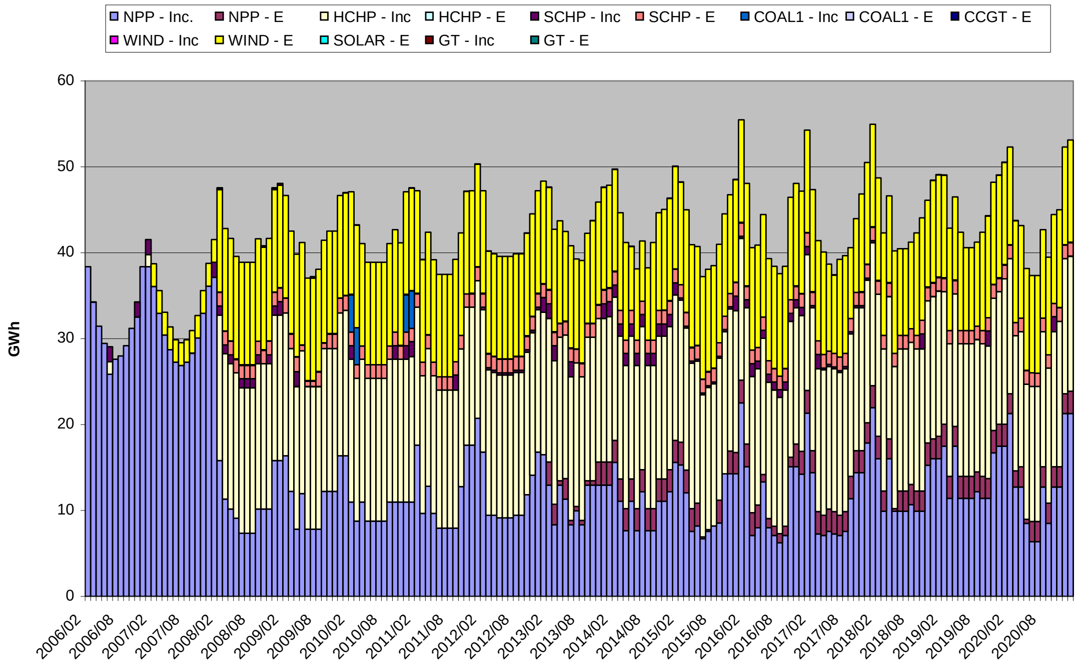
7 Appendix B: Investment planning, production and prices

	SOLAR_E	CCGT_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
Duopoly								
2006-2007		5.28	15.72	2.00	7.65	11.64	2.38	
Duopoly constrained by the EU ETS								
	SOLAR_E	CCGT_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
2006-2007			0.008	2.00	9.75			2.85
2007-2008			0.008		34.39			
2008-2009			0.008					
2009-2010			0.008					
Total			0.03	2.00	44.14			2.85
Duopoly benefiting from feed-in tariff								
	SOLAR_E	CCGT_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
2006-2007	14.56	3.29	7.85	2.00	20.82	1.53		
2007-2008	2.84				0.95			
2011-2012	0.00					1.37		
2015-2016	0.00				14.74			
2016-2017	0.35				0.73			
2017-2018	0.52				0.74			
2018-2019	0.57				1.53			
Total	18.83	3.29	7.85	2.00	39.53	2.90		

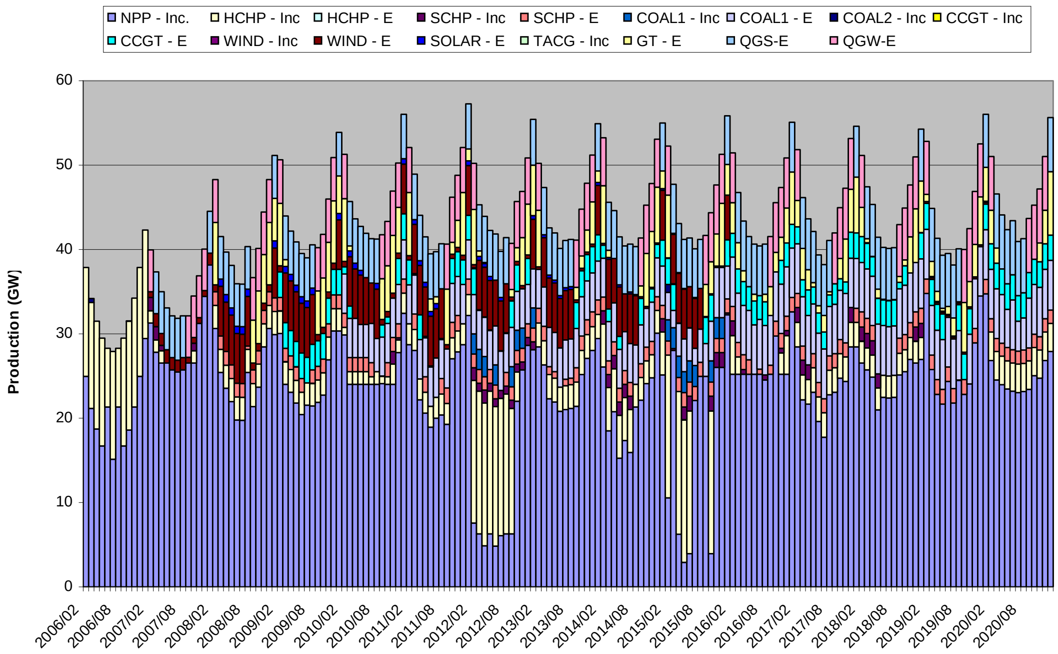
Investment planning (GW)



Production - duopoly case without environmental policy



Production - Duopoly constrained by the EU ETS



Production feed-in tariff

Share of the different technologies in the production

	NPP	COAL 1+2	CCGT	GT	FUEL	HCP+SCHP	WIND	SOLAR	ENR
2007	74.61%	0.01%	0.00%	0.00%		19.66%	5.73%	0.00%	25.38%
2008	71.28%	0.01%	0.00%	13.34%	2.04%	8.00%	5.34%	0.00%	13.34%
2009	59.12%	0.00%	10.68%	13.60%	1.63%	10.83%	4.13%	0.00%	14.96%
2010	56.91%	22.45%	3.76%	1.87%		10.58%	4.42%	0.00%	15.00%
2011	56.84%	24.23%	3.67%	0.12%		10.38%	4.76%	0.00%	15.14%
2012	57.48%	24.27%	6.79%	0.04%		9.04%	2.38%	0.00%	11.43%
2013	55.99%	22.82%	8.69%	0.00%		9.66%	2.85%	0.00%	12.51%
2014	56.25%	24.34%	5.84%	0.00%		9.99%	3.59%	0.00%	13.57%
2015	47.28%	24.08%	4.03%	0.00%		19.88%	4.73%	0.00%	24.61%
2016	54.74%	24.01%	3.64%	0.00%	0.20%	12.69%	4.72%	0.00%	17.41%
2017	54.21%	24.15%	5.18%	0.00%	0.20%	11.51%	4.75%	0.00%	16.26%
2018	55.57%	22.50%	9.45%	0.00%		11.28%	1.20%	0.00%	12.48%
2019	53.86%	21.54%	8.12%	0.00%		13.01%	3.46%	0.00%	16.47%
2020	57.39%	22.65%	5.81%	0.00%		9.46%	4.69%	0.00%	14.15%

Production - duopoly without environmental policy

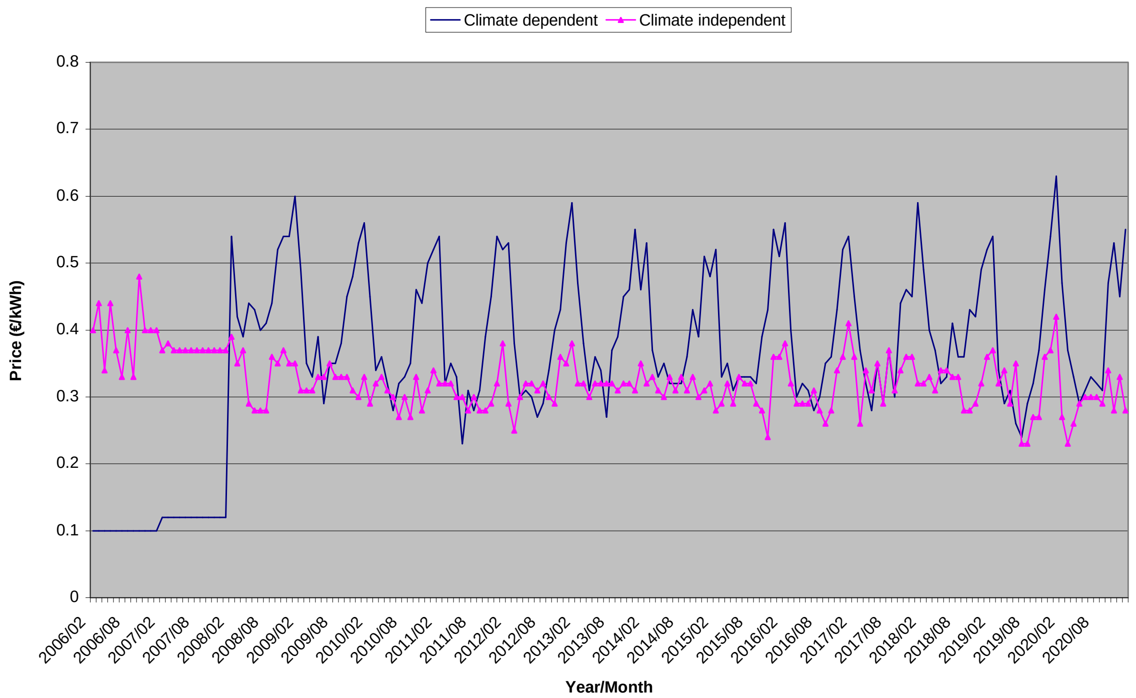
	NPP	COAL 1+2	CCGT	GT	FUEL	HCP+SCHP	WIND	SOLAR	ENR
2007	78.91%					5.47%	8.67%	6.95%	21.08%
2008	62.54%			6.46%		9.42%	13.38%	8.19%	30.99%
2009	55.84%	0.01%	6.32%	7.13%		9.45%	13.39%	7.86%	30.70%
2010	55.94%	8.98%	1.97%	6.44%		6.62%	12.72%	7.34%	26.68%
2011	53.46%	10.11%	3.34%	5.15%		7.69%	12.82%	7.42%	27.94%
2012	28.75%	13.25%	2.81%	4.20%		30.67%	12.90%	7.42%	50.99%
2013	53.56%	10.64%	2.27%	4.26%		8.72%	12.95%	7.60%	29.27%
2014	48.42%	10.13%	2.54%	5.44%		13.53%	12.49%	7.44%	33.46%
2015	37.45%	13.06%	2.83%	5.20%		21.33%	12.60%	7.53%	41.46%
2016	57.39%	12.54%	5.22%	4.76%		6.14%	6.39%	7.56%	20.09%
2017	53.00%	12.93%	4.76%	5.81%		10.24%	5.54%	7.73%	23.51%
2018	54.49%	12.87%	4.89%	4.30%		9.89%	5.63%	7.92%	23.44%
2019	58.80%	12.16%	4.61%	5.98%		3.74%	6.33%	8.39%	18.45%
2020	54.80%	11.71%	6.57%	2.88%		10.10%	5.83%	8.11%	24.03%

Figure 1: Production - duopoly benefiting from feed-in tariff.

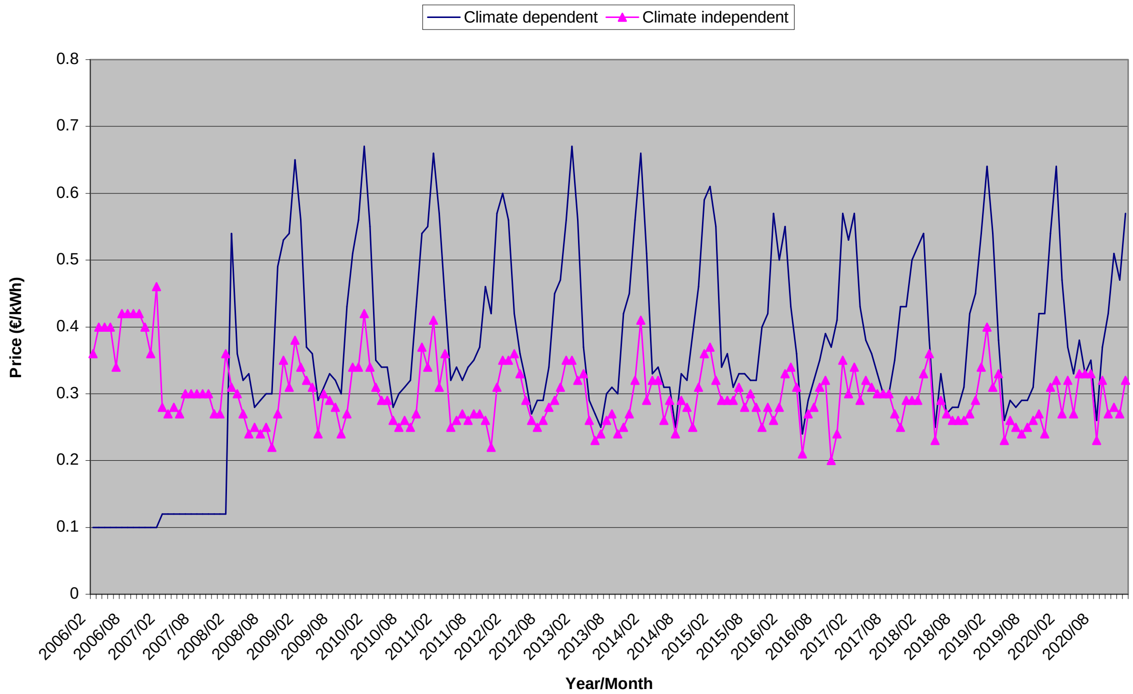
	NPP	COAL 1+2	CCGT	GT	FUEL	HCP+SCHP	WIND	SOLAR	ENR
2007	94.56%	0.01%	0.00%	0.00%	0.00%	0.81%	7.30%	0.00%	8.10%
2008	32.70%	0.00%	0.00%	0.13%	0.00%	46.18%	28.92%	0.00%	75.10%
2009	28.17%	0.01%	0.00%	0.09%	0.00%	43.78%	28.76%	0.00%	72.54%
2010	24.52%	2.54%	0.00%	0.02%	0.00%	43.43%	27.85%	0.00%	71.29%
2011	26.98%	0.84%	0.00%	0.03%	0.00%	41.42%	27.51%	0.00%	68.94%
2012	27.97%	0.00%	0.00%	0.03%	0.00%	42.48%	27.65%	0.00%	70.13%
2013	30.78%	0.00%	0.00%	0.03%	0.00%	44.82%	27.42%	0.00%	72.25%
2014	30.64%	0.00%	0.00%	0.02%	0.00%	45.51%	23.95%	0.00%	69.47%
2015	29.40%	0.00%	0.00%	0.02%	0.00%	42.60%	27.13%	0.00%	69.74%
2016	30.64%	0.00%	0.00%	0.01%	0.00%	41.99%	27.27%	0.00%	69.25%
2017	32.10%	0.00%	0.00%	0.01%	0.00%	42.61%	24.82%	0.00%	67.43%
2018	35.37%	0.00%	0.01%	0.01%	0.00%	42.56%	26.05%	0.00%	68.61%
2019	36.48%	0.00%	0.01%	0.02%	0.00%	38.51%	24.82%	0.00%	63.33%
2020	33.94%	0.00%	0.00%	0.01%	0.00%	39.99%	25.62%	0.00%	65.61%

Production - duopoly constrained by the EU ETS.

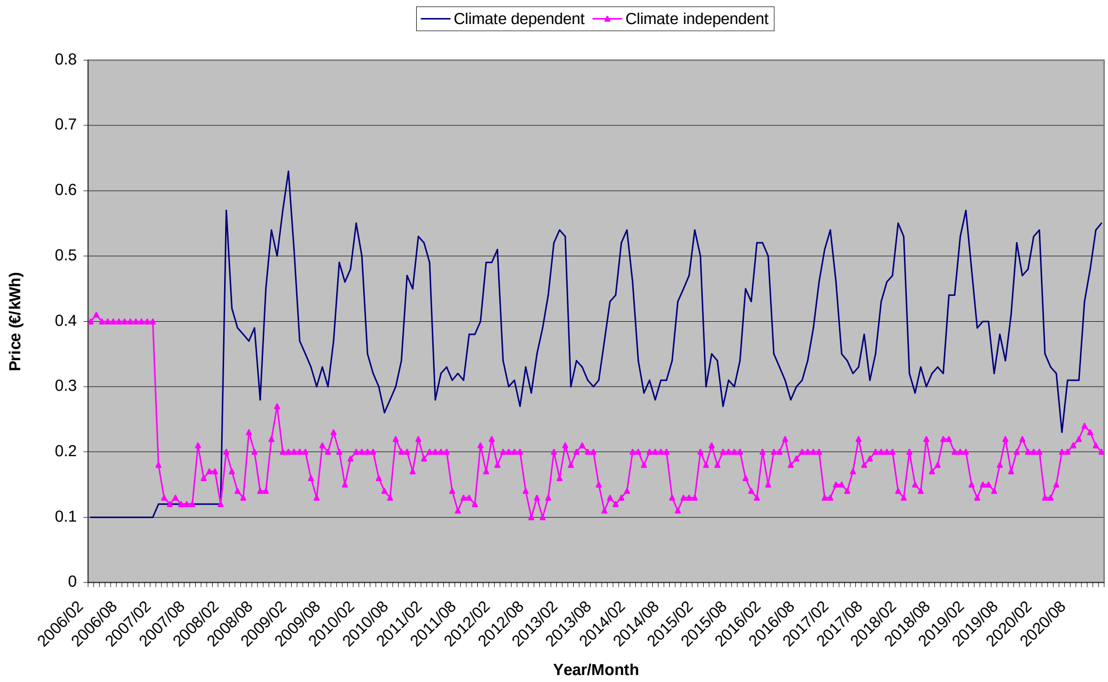
Prices



Prices - duopoly case without environmental policy



Prices - Duopoly constrained by the EU ETS



Prices - feed-in tariff

8 Appendix C: Analysis of sensitivity

We look at the impact of $\overline{S}(\theta)$ on the benefit of the different actors, the amount of CO_2 emissions and investment. We assume that $\overline{S}(\theta)$ may vary between 3.005 CO_2Gt and 4 CO_2Gt. We take as the reference the results obtained with $\overline{S}(\theta) = 3.005 \times 10^6$. When $\overline{S}(\theta) \leq 3.0005 \times 10^6$, we can note that the program is unfeasible. For the values of $\overline{S}(\theta)$ we used, the variations of the profit of the entrant compared to the reference range from -1.64% to 21.63% (see figure 2). For the incumbent (see figure 3), the interval is $[-5.58\% \; ; 1.88\%]$ and for the consumer (see figure 4), it is equal to $[-1.64\% \; ; 0.16\%]$. We could suggest as an intuition that the profit of the entrant and the incumbent do not vary in the same direction (see figure 5). The interval of variations in the social surplus is smaller. Indeed, it is $[-0.54\% \; ; 0\%]$. The non-positive values of this interval stresses that the baseline scenario for $\overline{S}(\theta)$ is better (in terms of profits) for the community than the scenarios studied.

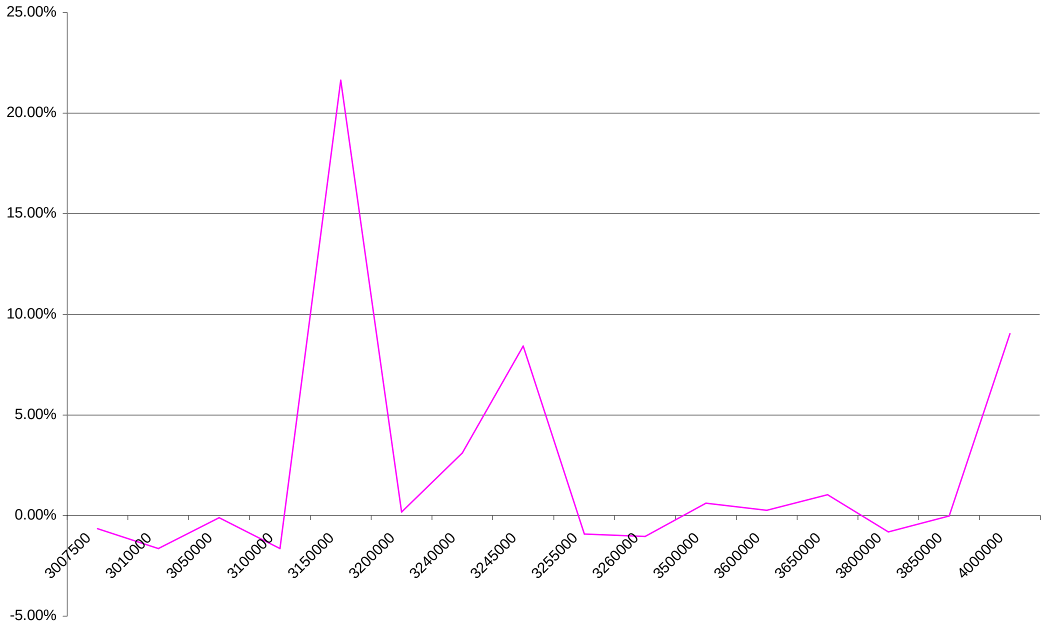


Figure 2: Variation of Entrant profit

What happens in terms of CO_2 emissions (see figures 6 and 7)? The variations of CO_2 emissions are not linear. They show a peak for the incumbent, which is closer in time when the CO_2 constraint is more restrictive.

The results depend on some unrealistic assumptions. Indeed, on the one hand, the entrant hasn't got any financing constraint, and on the other hand the investments in solar PV and windmills are not indefinitely scaleable (for examples, because of weather conditions, of hesitation of public opinion in the setting-up of these power plants in their neighborhood or of the incapacity of renewable technologies producers to supply the total demand of electricity producers). Nevertheless, the objective here is to determine the optimal investment by considering only the environmental constraints and to compare these cases to the one obtained without any environmental policy. We still look at the impact of constraints on investment in windmills and solar PV stations in the case of the quota policy. These constraints expressed as $\sum_a PEI\,(\theta, \text{solar}, a) \leq ls$ and $\sum_a PEI\,(\theta, \text{wind}, a) \leq lw$ are saturated if they are tight (see figure 8). The entrant substitutes windmills and solar PW stations to NPPs.

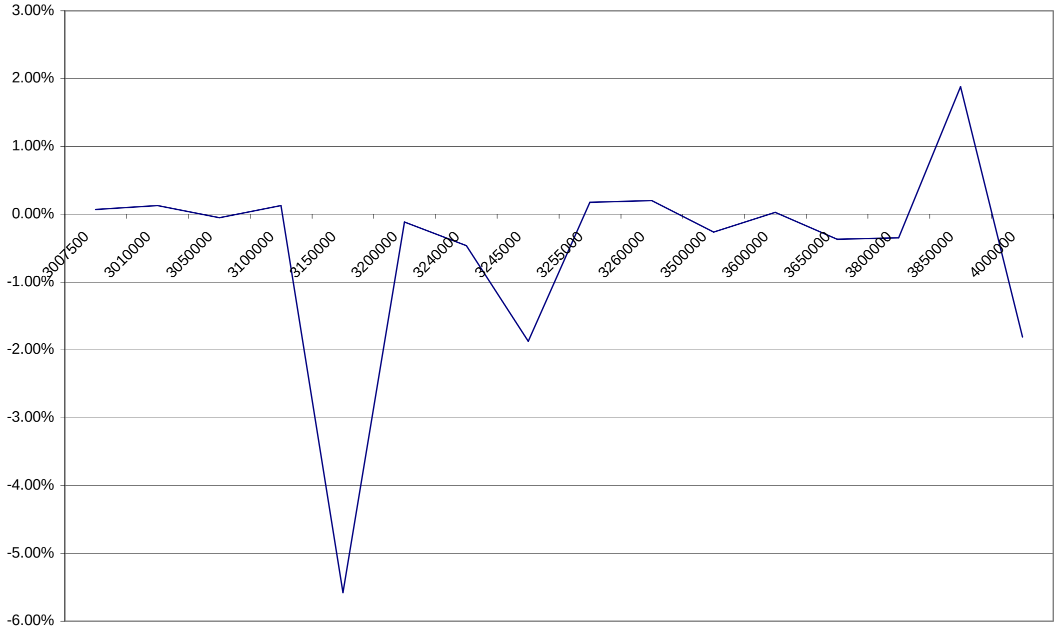


Figure 3: Variation of Incumbent profit

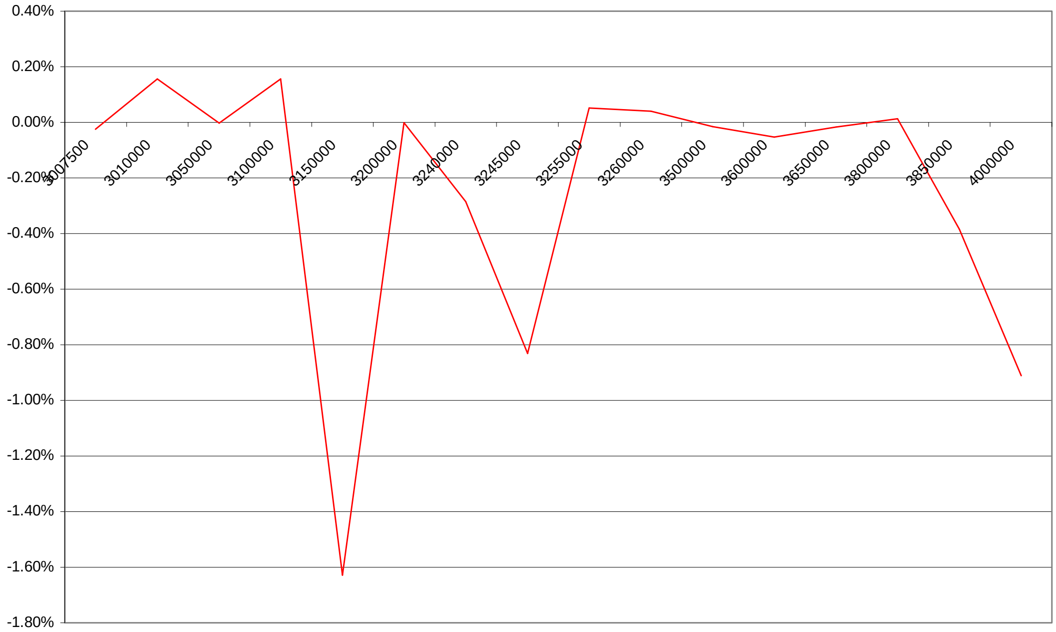


Figure 4: Variation of consumer surplus

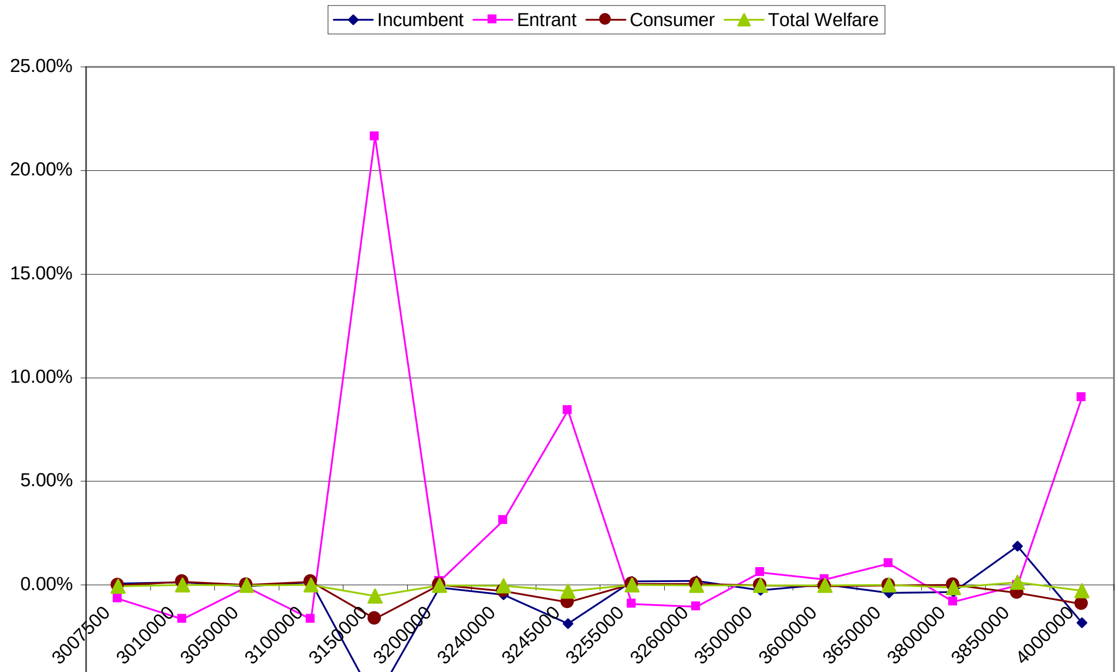


Figure 5: Variation of profits

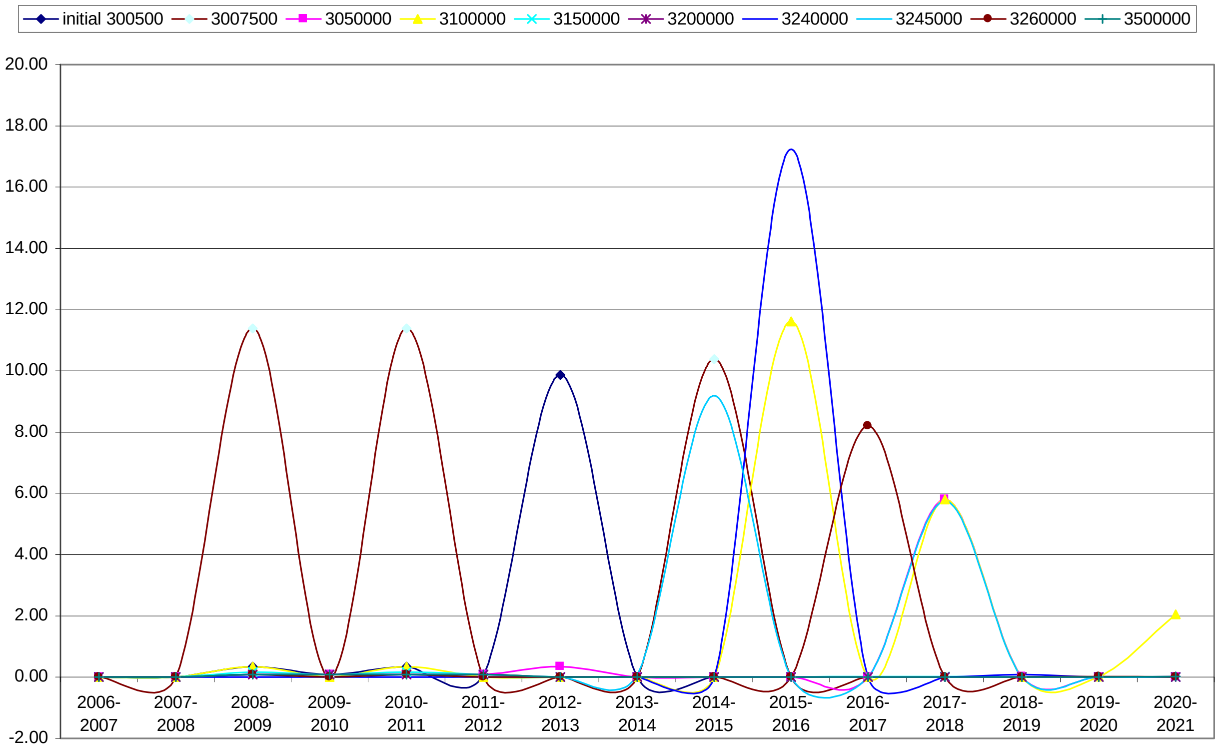


Figure 6: CO_2 emissions of the incumbent

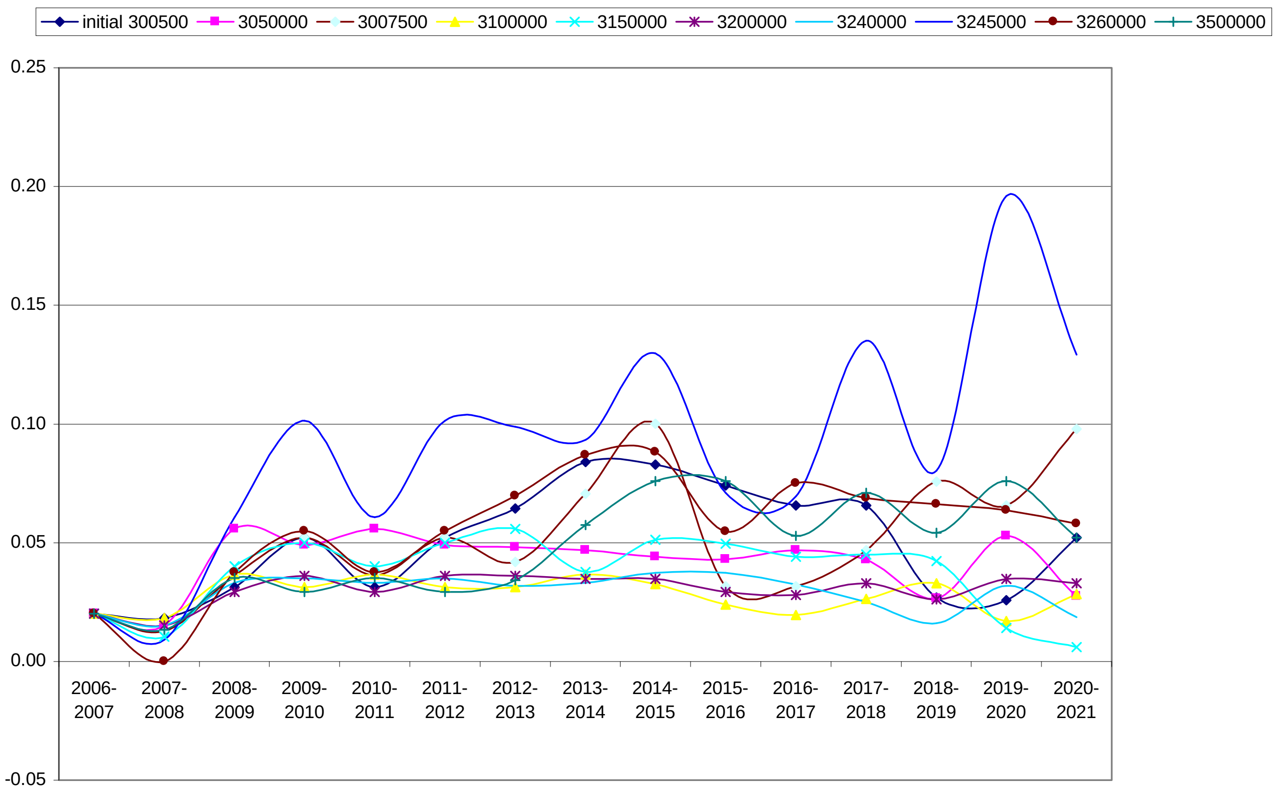


Figure 7: CO_2 emissions of the entrant

ls = 1 GW and lw = 1.5 GW

	CCGT_I	SOLAR_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
2006-2007		1.00		2.00	1.50		0.02	13.49
2007-2008		1.00			1.50		0.02	
2009-2010	0.0016	1.00			1.50		0.02	
2010-2011	0.0016	1.00			1.50		0.02	
2011-2012	0.0016	1.00			1.50			
2012-2013	0.0016				1.50			
2013-2014	0.0016							
2014-2015	0.0016							
2015-2016	0.0016							
2016-2017	0.0016							
2017-2018	0.0016							
Total	0.01		5.00	2.00	9.00		0.08	13.49

ls = 1 GW and lw = 2.5 GW

	CCGT_I	SOLAR_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
2006-2007		1.00		2.00	2.50		0.02	11.61
2007-2008		1.00			2.50		0.02	
2009-2010	0.0016	1.00			2.50		0.02	
2010-2011	0.0016	1.00			2.50		0.02	
2011-2012	0.0016				2.50			
2012-2013	0.0016				2.50			
2013-2014	0.0016							
2014-2015	0.0016							
2015-2016	0.0016							
2016-2017	0.0016							
2017-2018	0.0016							
Total	0.01	4.00		2.00	15.00		0.08	11.61

ls = 1 GW and lw = 4.5 GW

	CCGT_I	SOLAR_E	GT_E	SCHP_E	WIND_E	COAL1_E	FUEL_E	NPP_E
2006-2007		1.00		2.00	4.50		0.02	9.15
2007-2008		1.00			4.50		0.02	
2009-2010		1.00			4.50		0.02	
2010-2011		1.00			4.50		0.02	
2011-2012					4.50			
2012-2013					1.48			
Total		4.00		2.00	23.98		0.08	9.15

Figure 8: Investment planning (with wind and solar constraints)

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