FiME
LABORATOIRE COMMUN
DAUPHINE CREST EDF

LABORATOiRE DE FiNANCE
DES MARCHÉS DE L'ÉNERGiE

Environmental Policies in an Electricity Sector: Test on the French Electricity Sector

Corinne Chaton   Marie-Laure Guillerminet

Rapport de Recherche
RR-FiME-09-08
Décembre 2009

DAUPHINE UNIVERSITÉ PARIS

CREST Centre de Recherche en Économie et Statistique

EDF

ENVIRONMENTAL POLICIES IN AN ELECTRICITY SECTOR: TEST ON THE FRENCH ELECTRICITY SECTOR[+]

Corinne Chaton[*] and Marie-Laure Guillerminet[**]
[1] University of Alberta, Cabree
[2] Hamburg University, FNU

ABSTRACT

Feed-in Tariffs promoting renewable energy sources and quotas of CO_2 emissions have been implemented jointly in France to reduce CO_2 emissions. We develop on GAMS a supply-demand model applied to the electricity sector. Demand is uncertain and is characterized by load curves. We find that if both policies reduce emissions, feed-in tariffs involve a substantial extra-cost without significant gain for sure in terms of emissions.

Key words: CO_2 emissions; electricity generation; optimization.

JEL codes: C61; D81; L10; Q28; Q41.

1. INTRODUCTION

On January 23rd 2008, the European Commission adopted the "Energy-Climate Change" package, which must ensure the implementation of the European Council's decisions in March 2007. During this month in 2007, leaders of the European Union have agreed on: the reduction of at least 20%[1] of CO_2 emissions for the European Union (EU) by 2020 compared to 1990 levels, a share of at least 20%[2] renewable energy sources (RES) in total energy consumption of the EU in 2020 and a conditional 10% share of bio fuels in the consumption

---

[+] This work was supported by FiME, Laboratoire de Finance des Marchés de l'Energie (Dauphine, CREST, EDF R&D): www.fime-lab.org
* E - mail : cchaton@yahoo.fr
** E mail : ml_guillerminet@yahoo.fr
1 During the European Council in Brussels on December 11th and 12th 2008, an agreement has been reached on the "Energy-Climate Change" package. The 27 members states have also stated that if other countries which are signatories to the Convention on Climate Change increase efforts to reduce emissions, then the EU will reduce of at least 30% its emissions of greenhouse gases. The next international negotiations will be held in Copenhagen at the end of 2009.
2 The agreement reached during the European Council on December 11th and 12th 2008 is complete on the RES Directive.

of vehicles and the 20%[3] increase energy efficiency. The national objectives should take into account the current mix of energy and potential of different members states.

On one hand, imposing quotas is the most "direct" means to achieve the objective of 20% reduction of greenhouse gases (GHG) emissions. In 1997, the EU has ratified the Kyoto Protocol which sets legally binding targets for industrialized countries, to stabilize CO_2 concentration in the atmosphere. To achieve the objective of reducing the GHG emissions, the EU has implemented a marketplace for CO_2 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. On the other hand, feed-in tariffs are the most frequently used policy to promote RES, compared to green certificates, as it was established by the European Commission survey (2005). Comparisons on renewable energy promotion policies often conclude that feed-in tariffs incur substantial excess cost in terms of public subsidies 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 policymakers have to attach to reach other objectives[4] than the RSE 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 practice, 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.

But what is really the impact of these two instruments of environmental policies on CO_2 emissions?

In certain environment, Chaton and Guillerminet (2008) focus on the impact of quotas and tariffs on investment decisions in electricity generation capacity and CO_2 emissions by considering two market structures on the electricity sector: a regulated monopoly and a duopoly à la Cournot. Given the costs and demand functions they assume, competition increases CO_2 emissions as it is highlighted in Mansur (2007). In duopoly, only the EU ETS seems to be the efficient policy, combined with an energy efficiency 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 CO_2 emissions. The retained feed-in tariff policy is the most expensive policy in terms of "social welfare". Even if this policy seems to increase the "social welfare", feed-in tariffs increase the CSPE[5] which is paid by consumers by higher electricity prices and benefit only to new entrants. It is also less effective in terms of emissions reduction. Consequently, they note that, under certain assumptions, these two instruments may have contradictory effects in terms of CO_2 emissions. One of their contributions focus on the demand specification that allows to take into account not only the seasonality ignored in articles dealing with both competition and environmental policies, but also the price elasticity of demand. But their model is difficult to calibrate because of lack of information on these elasticities[6] .

3 which is not a binding constraint.
4 i.e. reduce additional market failures.
5 This amounts to a tax on energy which is not taken into account in this partial equilibrium model.
6 explained, among other things, the existence of regulated prices that persist.

We still consider that the demand is seasonal but we reject this assumption of the price elasticity of demand by taking demand specified by load duration curve, as in Chaton (1997), Chaton and Doucet (2003) or Madlener et al. (2005). By extending the two periods model of Chaton (1997)[7], we study the impact of two environmental policies on investment, production and emissions of CO_2, in a market where the operation of plants is based on the merit order[8] . We include the environmental policies, feed-in tariffs and quotas. We also assume that the environment is uncertain because of the energy efficiency policy. Then we calculate options generated by uncertainty and irreversibility of investment decisions. We define, calibrate and implement the model over the period 2006-2020 using French public data (cf. DGEMP) and GAMS. After solving backwards the dynamic program under uncertainty, we compare the results obtained from simulations, in terms of social cost, investment and CO_2 in four cases: without any environmental constraint, with quotas, with feed-in tariff and with both feed in tariffs and quotas. We conclude that the feed-in tariff policy induces substantial costs compared to gains that are not always significant in terms of avoided emissions. No investment was made before the third year, when the information is revealed about the scenario that will be made to ensure that investments are made. The value of the option of waiting is the largest with the quota policy.

2 MODEL AND CALIBRATION

2.1. Demand

We consider several periods (years) noted by $\theta = 1; : : : ; \Theta$. In order to take into account the demand's seasonality, each year is compound by subperiods, noted by $\tau = 1; : : : ; T$. The electricity consumed by thermosensitive consumers during the period θ; in the scenario ε of demand growth, is approximated by the upper integral of $\theta_{\tau\eta}(\tau; \theta; \varepsilon)$ where:

$$q_{th}(t,\theta,e)=\frac{4t^2\left(PKP(\theta,e)-BASE(\theta,e)\right)}{T^2}-\frac{4t\left(PKP(\theta,e)-BASE(\theta,e)\right)}{T}+PKP(\theta,e)$$

where $PKP(\theta, e)$ is the peak-load demand, $BASE(\theta, e)$ is the baseload demand, for period θ, when the scenario *e* of the demand growth is realized.

The energy consumed by the consumers whose demand is independent of weather during the year θ is equal to $8760\times q_{nth}(\theta,e)$.

Thus the quantity of the electricity demanded during one hour of the infraperiod τ during the period θ is equal to $q_{th}(\theta,e)+q_{nth}(\theta,e)$.

7 which determines the optimal investment by considering the thermal power stations of a monopoly when emission constraints are imposed.

8 by order of increasing production costs.

Application

We look at the period beginning on February 1st 2006 to January 31st 2021, i.e. Θ = 15. We assume that T = 12 (months): Thus we consider subperiods of 730 hours each. The first hour considered is the one of February 1st 2006. We assume that demands of the first two years of the study (from February 1st 2006 to January 31st 2008) are known and such that ΒΑΣΕ (1) = 25:67 GigaWatts hours (GWh), ΒΑΣΕ (2) = 25:7 GWh, ΠΚΠ (1) = 59:5 GWh, ΠΚΠ (2) = 59:55 GWh, $q_{nth}(1) = 17.5$ GWh, $q_{nth}(2) = 17.7$ GWh. Thus, demand from February 1st 2007 to January 31st 2008 (θ = 2) can be represented in Figure 1.

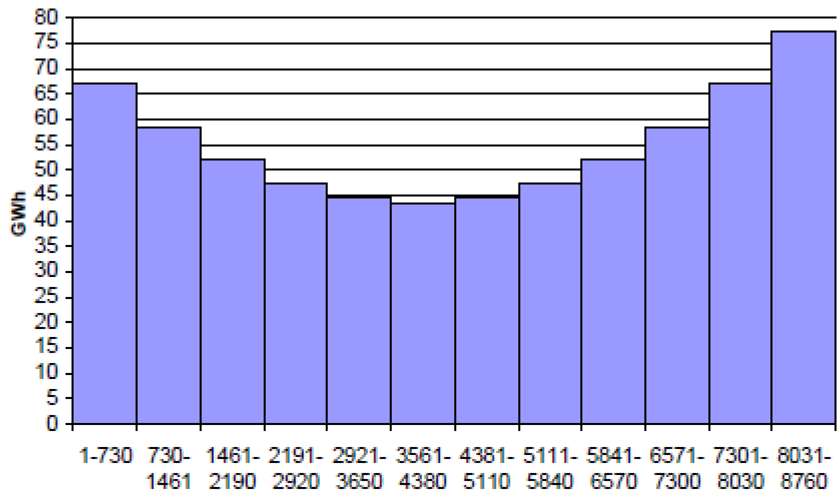


Figure 1. Total Demand from February 2007 to January 2008 equals approximately to 481 TWh.

Note that θ' is the date from which the demand is uncertain and in our application, θ'= 3.

We assume six scenarios of demand growth (see table 1, the annual demands being reported in table 2). The first four scenarios correspond to those released by RTE[9] (2007, 2008). The last two ones have been built assuming (such as in the CAS[10] report, 2007) a decrease in heating consumption of 0:8% (respectively 1:2%) from 2010 that we characterize by a drop in peak-load demand of consumers whose demand depends on weather of 0:42% (resp. of 0:64%) with an increase in the baseload demand and the demand of consumers whose are independent on weather of 0:9% from 2008 to 2010 and 0:7% from 2010 to 2020.

Table 1. Scenarios of demand growth

---

[9] Réseau de Transport d'Electricité, i.e. the French transport operator.

[10] Centre d'Analyse Stratégique, i.e. an organization directly affiliated to the Prime Minister.

State of Nature or Scenario	**Rate of average growth in %**	
	2008-2010	2010-2020
1	1.3	1
2	0.9	0.7
3	0.7	0.5
4	1.5	1.2
5	0.9	0.7[11] -0.424[12]
6	0.9	0.7[11] -0.636[12]

Table 2. Annual Demands in TWh

Years	State 1	State 2	State 3	State 4	State 5	State 6
2007	481	481	481	481	481	481
2008	486	485	484	487	485	485
2009	493	489	487	494	489	489
2010	499	493	491	502	493	493
2011	504	497	493	508	495	495
2012	509	500	496	514	497	496
2013	514	504	498	520	498	497
2014	519	507	501	527	500	498
2015	525	511	503	533	501	499
2016	530	515	506	539	503	501
2017	535	518	508	546	504	502
2018	541	522	511	552	506	503
2019	546	525	513	559	507	504
2020	551	529	516	566	509	505
Total	7233	7076	6988	7328	6968	6948

In what follows, for $\theta \geq \theta'$, we assume:

$$PKP(\theta,e) = (1+\tau_{1,e})^{\theta-2} PKP(2) H(5-\theta) + (1+\tau_{1,e})^3 (1+\tau_{2,e})^{\theta-3} PKP(2) H(\theta-5), \forall e,$$

$$BASE(\theta,e) = (1+\tau_{1,e})^{\theta-2} BASE(2) H(5-\theta) + (1+\tau_{1,e})^3 (1+\tau_{2,e})^{\theta-3} BASE(2) H(\theta-5), \forall e$$

where H is the Heaviside function and

$$q_{nth}(\theta,e) = (1+\tau_{1,e})^{\theta-2} q_{nth}(2) H(5-\theta) + (1+\tau_{1,e})^3 (1+\tau_{2,e})^{\theta-3} q_{nth}(2) H(\theta-5), \forall e.$$

2.2. Supply

Note X the number of generating technologies c. In $\theta = 1$, generative capacities $PED(1,c) \in \Re^C$ have already been installed. These technologies operate according their merit

11 for baseload generation and q_{nth}.
12 for the decrease of peak-load demand of consumers who are weather sensitive, i.e. of *PKP*.

order. Thus, the optimization program is the minimization of expected total cost $CT(.)$ for the different scenarios of demand growth.

$$
\begin{aligned}
CT(.) = & \sum_{\theta=1}^{\theta'-1}\sum_{c=1}^{C}\left(\eta_c PED(\theta,c)+\iota_c PEI(\theta,c)\right)(1+r)^{1-\theta} \\
& +\sum_{\theta=1}^{\theta'-1}\sum_{t=1}^{T}\sum_{d=1}^{T}\sum_{c=1}^{C}\left(\varpi_c + p_c r_c\right)PEF(\theta,t,d,c)\frac{8760}{T(1+r)^{\theta-1}} \\
& +\sum_{\theta=\theta'}^{\Theta}\sum_{e}\sum_{c=1}^{C}P(e)\left(\eta_c PED'(\theta,c,e)+\iota_c PEI'(\theta,c,e)\right)(1+r)^{1-\theta} \\
& +\sum_{\theta=\theta'}^{\Theta}\sum_{e}\sum_{t=1}^{T}\sum_{d=1}^{T}\sum_{c=1}^{C}P(e)\left(\varpi_c + p_c r_c\right)PEF'(\theta,t,d,c,e)\frac{8760}{T(1+r)^{\theta-1}}
\end{aligned}
$$

where:

$P(e)$ is the probability that the scenario *e* is realized;

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 is the price of the fuel used by the power station type *c*;

$PEF(\theta,t,d,c)$ (resp. $PEF'(\theta,t,d,c,e)$) is the supplied electric power by the plant of type *c* running during the infraperiod *t* with (*d* - 1) the other subperiods, *d* integer such that $1 \le d \le T$ (resp. in the state of nature *e*);

$PEI(\theta,c)$ (resp. $PEI'(\theta,c,e)$) is the capacity invested in the technology *c* during the period θ (resp. and in the state of nature *e*);

$PED(\theta,c)$ (resp. $PED'(\theta,c,e)$) is the amount of the existing capacity of station type *c* during the period θ (resp. and in the state of nature *e*), which is defined by:

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

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

with β_c is the construction duration of station type χ and $DEC(\theta,c)$ the amount of decommissioning for technology χ during the period θ.

Application (cf. DGEMP, 2003)

We consider 10 technologies (χαρδ(Χ) =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 stations (SOLAR), fuel power plants (FUEL) and gas turbines (GTs). We do not consider biomass[13]. Moreover, we do not take into

[13] This is 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. It should also take into account possible conflicts of use.

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 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.

We constraint the potential annual investment in windmills, solar PV stations and small hydroelectric plants: 0.5 GW for solar PV stations and 2 GW for windmills[14]. We consider that the remaining potential to invest in small hydroelectric plants is a maximum of 2 GW, knowing that the sites for large hydropower plants are saturated.

The investment costs (in €/kWe), the construction duration and initial production capacities (in GW) in the different technologies are summarized in Table 3.

Table 3. Investment costs (in ε/kW), construction duration and initial production capacities (in GW)

	Investment Cost (€/KW)	Initial production capacities (GW)	Construction duration (years)
NPP	1663	62.84	7
HCHP		18.8	4
SCHP	1896	1.8	2
COAL1	1400	7.07	5
COAL2	1437	0.99	5
CCGT	559		4
WIND	922	0.23	1
SOLAR	4000		1
FUEL	328	7.52	2
GT	328	0.23	2

We assume that there is no uncertainty about fuel prices and the results are based on price assumptions shown in Table 4.

Table 4. Fuel prices

	Coal \$/t	Gas[15] \$/Mbtu	Fuel[16] €/m^3
2006/02-2008/01	30	4	177.3
2008/02-2009/01	160	12	1100

[14] These constraints express, among other things, the limited capacity of the producers of solar panels and wind turbines to supply demand which rises rapidly.

[15] with a growth rate of 3% per year since 2009/02.

[16] with a growth rate of 5% per year since 2009/02.

2.2.1. Constraints

First, the supply constraints state that for each period θ and for each state of nature *e*, the generative capacity of the technology *c* cannot exceed the installed one[17]. So for any θ in the interval of study

$$\sum_{d=1}^{T}\frac{\sum_{t=1}^{T} PEF'(\theta,t,d,c,e)}{d \times DISP(d,c)} \leq PED(\theta,c,e), \quad \forall c,e$$

with $DISP(d,c)$ the availability factor[18] of a power station running with technology *c*. This factor is dependent not only on the technology χ but also on the hour of functioning during a year $(d \times 8760/T)$ and on the weather conditions. We assume that

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

The second group of constraints is inherent in the definition of ΠΕΦ(.) (cf. Chaton, 1997, for demonstration): for any θ in the interval of study

$$\sum_{t=1}^{T} PEF'(\theta,t,d,c,e) - d.PEF'(\theta,k,d,c,e) \geq 0, \quad \forall \theta \geq \theta', k, d, c, e.$$

Finally the total supplied power during the subperiods τ must be superior or equal to the demanded power during this subperiod. So for any θ in the interval of study

$$\sum_{d=1}^{T}\sum_{c=1}^{C} PEF'(\theta,t,d,c,e) \geq q_{th}(\theta,t,e) + q_{nth}(\theta,e), \quad \forall \theta \geq \theta', t, e.$$

Application

The values of the parameters of the availability function, $DISP(d,c)$, are dependent on the number of hours of operation. They are summarized in Table 5. We assumed that the solar PV stations do not produce during March, October, November, December, January and February.

---

17 $\sum_{t=1}^{T} PEF(\theta,t,d,c) \Big/ \left(d \times DISP(d,c)\right)$ is the total of the capacities actually needed for the production of the plants running with the technology *c* during *d* subperiods.

18 This rate is equal to (1 - maintenance rate) × (1 - unscheduled outage rate). The latter is random. Yet, here, one passes over the disturbance term.

Table 5. Parameters of the availability function

Number of the operating hours in a year d.8760/12	≤ 1000 hours		[1000; 4000] hours		> 4000 hours	
Technology	α_d	β_d	α_d	β_d	α_d	β_d
MPP	0.984	$-9.3661\ 10^{-06}$	0.984	$-9.3661\ 10^{-06}$	0.984	$-9.3661\ 10^{-06}$
HCHP	0.9	0	0.9	0	0.9	0
SCHP	0.97	0	0.97	0	1.103	$-3.67\ 10^{-05}$
COAL1	0.945	$-7.275\ 10^{-06}$	0.945	$-7.275\ 10^{-06}$	0.935	$-3.67\ 10^{-06}$
COAL2	0.945	$-7.275\ 10^{-06}$	0.945	$-7.275\ 10^{-06}$	0.935	$-3.67\ 10^{-06}$
CCGT	0.956	$-4.15\ 10^{-06}$	0.956	$-4.152\ 10^{-06}$	0.956	$-4.15\ 10^{-06}$
WIND	0.27	0	0.27	0	0.27	0
SOLAR	0.34	0	0.34	0	0.34	0
FUEL	0.97	0	0.973	$-8.84\ 10^{-06}$	0.973	$-8.835\ 10^{-06}$
GT	0.97	0	0.973	$-8.84\ 10^{-06}$	0.973	$-8.835\ 10^{-06}$

2.2.2. Feed-in Tariffs

These are direct subsidies that are net of total expected costs. Thus, the following terms should be added to the objective function when this policy is studied.

$$-\sum_{\theta=1}^{\theta'-1}\sum_{t=1}^{T}\sum_{d=1}^{T}\left(P_{GS}(\theta,t,d)Q_{GS}(\theta,t,d)+P_{GW}(\theta,t,d)Q_{GW}(\theta,t,d)\right)\frac{8760}{T(1+r)^{\theta-1}}$$
$$-\sum_{\theta=\theta'}^{\Theta}\sum_{e}\sum_{t=1}^{T}\sum_{d=1}^{T}P(e)\left(P_{GS}(\theta,t,d,e)Q'_{GS}(\theta,t,d,e)+P_{GW}(\theta,t,d,e)Q'_{GW}(\theta,t,d,e)\right)\frac{8760}{T(1+r)^{\theta-1}}$$

where $P_{GS}(.)$ and $P_{GW}(.)$ are the feed-in tariffs for the production of solar PV stations and windmills; $Q_{GS}(.)$ and $Q_{GW}(.)$ are the respective quantities produced and paid to these feed-in tariffs.

Application

According to the Journal Officiel of 10 July 2006, the price at which EDF is obliged, by contract, to purchase each kWh when the operator of a site has obtained permission to produce electricity are the following. The tariff for solar PV station is 300 € / MWh for 15 years. For the windmills it is equal to 82 € / MWh for 10 years and during the next 5 years, to:

- 28 € / MWh for wind turbines that produce for at least 3650 hours during one year,
- 68 € / MWh if their production is between 2190 and 3650 hours and
- 82 € / MWh if they produce less than 2190 hours.

2.2.3. The EU ETS

The European Union Emission Trading System (EU ETS) is the largest multi-national, emissions trading scheme in the world. The EU ETS is a quota market which begun in 2005 and which is regulated in application of Directive 2003/87/EC. The EU ETS currently covers more than 10,000 installations in the energy and industrial sectors which are collectively responsible for close to half of the EU's emissions of CO_2 and 40% of its total GHG emissions.

Since January 2008, the 2nd Trading Period is under way which will last until December 2012. Currently, the installations get the allowances for free from the EU member states' governments. Besides receiving this initial allocation on a plant-by-plant basis, an operator may purchase EU allowances from others (installations, traders, the government). If an installation has received more free allowances than it needs, it may sell them to anybody.

The EU ETS restricts in particular CO_2 emissions of the European electricity sectors. So constraints (i.e. quotas allowances) are established at the national level by National Allocation Plans (NAPs) for the electricity sector. Thus during each year, θ, CO_2 emissions must be below a certain threshold $S(\theta, e)$, free quota allowances in France[19] on the basis of historical emissions for existing plants ("grandfathering") and of the Best Available Technology (BAT) which is CCGTs, for new power plants. In France, the NAP sets a constraint of 35.92 million tons of CO_2 per year ($MtCO_2$/y) for the first phase (2005-2007). It strengthens it for the second phase (2008-2012) with a decrease to 25.592 $MtCO_2$/y. A *priori* these free allowances will not continue. During the Senate debates on the adoption of the Law on environmental responsibility of 28-30 May 2008, a sub-amendment was introduced referring to the opportunity to auction 25% of free allowances allocated to electricity firms in NAP 2 (2008-2013), in order to compensate for the low level of the quota reserve for new entrants. This sub-amendment was then rejected. Furthermore the European Council of 11 and 12 December 2008 reached agreement on the "Energy-Climate Change" package. The elements of the final compromise on the ETS Directive put forward for the electricity sector an exception[20] to the possible auctioning of all allowances in 2013. The volume of auctioning should be at least 30% in 2013, increasing gradually to 100% by 2020, with a rendez-vous clause 2 years before the end of each exemption. The quota allowances are still managed nationally, contrary to what was announced in January 2008, when the European Commission proposed a number of changes to the scheme, including centralized allocation (no more national allocation plans) by a EU authority.

The allocations are sectoral. Then 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

---

[19] 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 Levy (2005) for a good description of the EU ETS.

[20] pursuant to article 10c of the Directive.

allocated excess permits and banking[21] 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[22] on the functioning of the CO_2 trading market, we will take into account this market with exogenous and random prices of CO_2 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 $MtCO_2$/y (resp. 14.4 $MtCO_2$/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[23] according to the formula for the second phase (NAP 2). Both generators are submitted to an additional constraint which represents the policy with quotas.

During each period (year) during the NAP 2 (for 2008/02 to 2012/01) and after[24] , emissions must be lower than a threshold of quotas:

$$\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF'(\theta,t,d,c,e)}{d} \leq S(\theta,e), \forall \theta, e \tag{1}$$

where φ_c is the emission factor of station χ and $S(\theta,e)$ (in CO_2 tons, tCO_2) are the constant emissions thresholds during the period θ, defined by (3). In reality, if the producer has not exhausted its quota, it may be postponed and thus increase the quota that will be allocated in the following year. Consequently, (1) must be replaced by

$$\begin{aligned}\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF'(\theta,t,d,c,e)}{d} &\leq S(\theta,e) + S(\theta-1,e) \\ &-\sum_{d=1}^{T}\sum_{c=1}^{C}\varphi_c \frac{\sum_{t=1}^{T} PEF'(\theta-1,t,d,c,e)}{d}, \quad \forall \theta, e,\end{aligned} \tag{2}$$

$$\begin{aligned}S(\theta+1,e) = &\sum_{d=1}^{T}\sum_{c=1}^{C}(\rho.g(1-0.025))\varphi_c \frac{\sum_{t=1}^{T} PEF'(\theta,t,d,c,e)}{d} \\ &+\sum_{c=1}^{C} h_c \Phi(\theta,c) PEI'(\theta-\beta_c,c,e), \forall \theta, e\end{aligned} \tag{3}$$

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

22 Firms have been over-allocated during the NAP 1 phase.

23 as in Gilbert et al. (2006): "The European Commission states that the objective of the scheme [EU ETS] is "to promote reductions of greenhouse gas emissions 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."

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

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

For the second phase, we do not take into account the formula described above where the producers receives their quotas according to their amount of investment and also their production planning for the following reason. The producer may have an interest to make a lot of emissions in the early years (saturates (1)) 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 (3) by the following equations.

$$S(\theta+1, e) = \lambda S(\theta, e) + \sum_{c=1}^{C} h_c \Phi(\theta, CCGT) PEI'(\theta - \beta_c, c, e)\frac{8760}{T}, \forall \theta, e. \tag{4}$$

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:

$$\sum_{c=1}^{C}\sum_{t=\beta_c}^{T} h_c \Phi(\theta, CCGT) PEI'(\theta - \beta_c, c, e)\frac{8760}{T} \leq \bar{S}(\theta), \forall \theta, e. \tag{5}$$

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

Application

By hypothesis, at the beginning of the period, the initial cap is 38.95 million tons (Mt) of CO_2, or $S(1) = 38.95 \times 10^6$. Without investment, the quota reduction is equal to 20%, then $\lambda = 0.8$. The amount of additional allowances can not exceed 3 million tons of CO_2, thus $\bar{S}(\theta) = 3 \times 10^6$. For calibrations, we assume $\Phi(\theta, CCGT) = 365$ gCO_2/kWh and we consider five polluting technologies: CCGT, COAL1, COAL2, GT and FUEL with

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

3 Results and Concluding Remarks

Both policies reduce CO_2 emissions (see Table 7).

Without any environmental policy, investments are made only in the two scenarios of "high" demand growth, scenarios 1 and 4 (see Table 6). The new installed capacity run with gas technologies. Investments are made in 2018 in the state of nature 1 (e1) and from 2015 to 2018 in the state of nature 4 (e4), see appendix 5.1: "Schedule of investment".

The implementation of environmental policies involves the abandonment of these investments. Indeed, investment in gas turbine and combined cycle gas turbine is only marginal (10 MW). For the two scenarios of the lowest demand growth (e5 and e6), investment is made only when feed-in tariffs are set up, combined or not with the quota policy. Because of the adopted modeling of this policy, the constraints on investment in solar PV stations (7 GW, i.e. 0.5 GW / year) and windmills (28 GW, i.e. 2GW/year) are saturated. Indeed, the producer receives subsidies, which enable it to cover its costs greatly when he invests in these two technologies. Note that over the period studied, the expected additional cost generated by feed-in tariff[25] is the largest (about 460%). They have the effect of introducing solar energy in the mix with a share in the total production of around 1% (see Table 7). Increasing the share of wind energy is more consistent. This obviously entails a reduction of CO_2 in the order of 33% to 50% in states 1 and 4, reduction which becomes almost equal to zero in states 2, 3, 5 and 6. As shown by the appendix 5.2: "Annual CO_2 emissions", the feed-in tariff policy slows the growth of CO_2 emissions. In 2020, for the scenario of the highest demand growth (e4), the emissions level achieved by this policy (3.67 $MtCO_2$) is close to the maximum reached with the quota policy in 2013 (4 $MtCO_2$). While the feed-in tariff policy immediately slows the growth of CO_2 emissions, it is not the case for the quota policy: it is not until 2013 that the effects of this policy begin through a CO_2 emissions reduction, to reach in 2020 values between 0.08 $MtCO_2$ and 0.43 $MtCO_2$.

So when the two high scenarios of demand growth are realized (e1 and e4), we can wonder if this additional cost is really justified when the only objective is to reduce CO_2. Indeed, a policy of quotas may lead[26] to the reduction of emissions of the same magnitude but with a much smaller (7% vs 459%) additional cost. Since the emission reductions are important in the first four scenarios, a quota policy would not be enough? We may also question the need to impose such a policy if one of two scenarios where demand growth is weak happens.

[25] cost of subsidy for the use of expensive technologies.

[26] if one of these two scenarios is true.

Table 6. Investment and expected total cost

Period from 2006/02 to 2021/01	**No environmental constraint**	**Quota**	**Feed in Tariff**	**Feed in Tariff and Quota**
Cost in billion €	78.42	84.14	438	440
Cost in variation (%)	-	7.20%	459.15%	460.60%
Investment (GW)				
State 1(e1)				
NPP		8.82		0.94
SCHP		2.00		2.00
CCGT	0.62	0.01		0.01
GT	3.78	0.01		0.01
SOLAR			7.00	7.00
WIND		2.00	28.00	28.00
State 2(e2)	No Investment			
NPP		4.92		
SCHP		2.00		
CCGT		0.01		
GT		0.01		
SOLAR			7.00	7.00
WIND		2.00	28.00	28.00
State 3(e3)	No Investment			
NPP		2.58		
SCHP		2.00		
CCGT		0.01		
GT		0.01		
SOLAR			7.00	7.00
WIND		2.00	28.00	28.00
State 4(e4)				
NPP		11.32		3.44
SCHP		2.00		2.00
CCGT	2.32	0.01		0.01
GT	4.62	0.01		0.01
SOLAR			7.00	7.00
WIND		2.00	28.00	28.00
State 5(e5)	No Investment			
SCHP		0.28		
CCGT		0.01		
SOLAR			7.00	7.00
WIND			28.00	28.00
State 6(e6)	No Investment	No Investment		
SOLAR			7.00	7.00
WIND			28.00	28.00

Table 7. CO_2 emissions, consumption and production

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	48.15	23.39	15.95	11.03
Consumption	7706	7706	7706	7706
NPP	68.40%	68.69%	61.13%	61.37%
HCHP and SCHP	30.64%	30.75%	31.03%	30.87%
CCGT	0.03%			
GT	0.10%			
COAL1 and COAL2	0.73%	0.39%	0.27%	0.18%
FUEL				
SOLAR			1.02%	1.02%
WIND	0.10%	0.17%	6.55%	6.56%

State 1

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	35.18	19.00	0.69	0.73
Consumption	7561	7561	7561	7561
NPP	67.56%	67.89%	60.41%	60.41%
HCHP and SCHP	31.73%	31.58%	31.86%	31.86%
CCGT	0.09%	0.16%		
GT				
COAL1 and COAL2	0.60%	0.35%	0.02%	0.02%
FUEL	0.01%			
SOLAR			1.03%	1.03%
WIND	0.01%	0.01%	6.68%	6.68%

State 2

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	26.59	16.23	0	0
Consumption	7470		7470	7470
NPP	67.16%	67.44%	59.94%	59.94%
HCHP and SCHP	32.24%	32.08%	32.25%	32.25%
CCGT				
GT				
COAL1 and COAL2	0.49%	0.31%	0.01%	0.01%
FUEL				
SOLAR			1.05%	1.05%
WIND	0.11%	0.17%	6.76%	6.76%

State 3

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	58.42	25.43	25.23	14.67
Consumption	7819	7819	7819	7819
NPP	68.49%	68.51%	61.31%	61.70%
HCHP and SCHP	30.32%	30.87%	30.81%	30.59%
CCGT	0.12%			
GT	0.12%			
COAL1 and COAL2	0.85%	0.45%	0.42%	0.25%
FUEL				
SOLAR			1.00%	1.00%
WIND	0.10%	0.16%	6.46%	6.46%

State 4

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	13.35	12.73	0.05	0.03
Consumption	7450	7450	7450	7450
NPP	67.30%	67.46%	59.83%	59.83%
HCHP and SCHP	32.33%	32.17%	32.34%	32.34%
CCGT				
GT				
COAL1 and COAL2	0.26%	0.25%	0.01%	0.01%
FUEL				
SOLAR			1.05%	1.05%
WIND	0.11%	0.11%	6.78%	6.78%

State 5

From 2006/02 to 2021/01	No environmental constraint	Quotas	Feed-in tariff	Feed-in tariff and Quotas
CO_2 emissions (Mt)	9.34	9.34	0.05	0.04
Consumption	7429	7429	7429	7429
NPP	67.28%	67.28%	59.72%	59.72%
HCHP and SCHP	32.42%	32.42%	32.43%	32.43%
CCGT				
GT				
COAL1 and COAL2	0.20%	0.20%	0.01%	0.01%
FUEL				
SOLAR			1.05%	1.05%
WIND	0.11%	0.11%	6.80%	6.80%

State 6

In the case of the two highest demand growth scenarios (e1 to e4), the quota policy without any feed-in tariff boosts investment in nuclear power plants and helps to saturate the constraint of investment in small hydroelectric plants. Whatever the demand scenario and the considered policy are, the share of hydropower in the production is relatively stable (between

30.32% and 32.43%) and the nuclear power varies between 59.72%[27] and 68.49%[28] . Feed-in tariffs facilitate the integration of renewable energies, especially wind power, in generation at the expense of nuclear power plants. We confirm this assertion by a sensitivity analysis on the duration of feed-in tariffs.

For each policy, no investment is made the first two years. It is not until the third year, when the information is revealed about the scenario that will be realized, to ensure that investments are made. We calculated the value of the option to wait for more information on future conditions, i.e. more information on demand (for more information on this literature see Dixit and Pindyck, 1994). The option values are: ε 567 million if no environmental policy is imposed, ε 8660 million under a quota policy, ε 1.16 million under feed-in tariff and ε 3680 million under both quota policy and feed-in tariff. Under feed-in tariff, the costs of RES are largely recovered and investments are identical[29] regardless of the state of nature that will happen, because the value of the option of waiting is lower. As against, the value of the option of waiting is higher when quota policy is imposed, since the investment will vary considerably depending on the state of nature.

Unlike Chaton and Guilleminet (2008), the effects of the two policies are not contradictory. One of the differences between the two approaches is based on the specification of demand, and more specifically on the inclusion or not of a price elasticity of demand. An extension would consider the impact of this specification on emissions.

ACNKOWLEDGEMENTS

We thank J.-M. Charpin as well as participants at the Annual Congress of AFSE (2008) and the Workshop "Real Options in Energy Economics" at ZEW (2008) for their remarks and comments. All errors remain ours.

4. REFERENCES

Böhringer C, Hoffman T, Rutherford T F. Alternative Strategies for Promoting Renewable Energy in EU Electricity Markets. Applied Economics Quarterly Supplement 2007; 58; 9-26.

Butter L, Neuhoff K. Comparison of Feed in Tariff, Quota and Auction Mechanisms to Support Wind Power Development. Renewable Energy 2008; 33 (8); 1854-1867.

Centre d'Analyse Stratégique (CAS). Les perspectives énergétiques de la France à l'horizon 2020-2050. Rapports et documents « Développement durable »; 2007.

Chaton C. Fuel price and demand uncertainties and investment in an electricity model: a two-period model. *Journal of Energy and Development*, 1997; 23 (1); 29-58.

Chaton C, Doucet J. Uncertainty and Investment in Electricity Generation With an Application to the Case of Hydro-Québec. *Annals of Operations Research*, 2003; 120; 59-80.

[27] under feed-in tariff policy.

[28] under a scenario without any environmental policy and with the highest demand growth.

[29] i.e. saturation constraints for investment in wind and solar power.

Chaton C, Guillerminet M.-L. Competition and environmental policies in an electricity sector. mimeo. 2008.

Dixit A.K, Pindyck R.S. Investment under Uncertainty. Princeton University Press; 1994.

DGEMP. Les coûts de référence de la production électrique. DGEMP/DIDEME/SD6, Ministère de l'Economie, des Finances et de l'Industrie; 2003.

Commission Européenne. The support of electricity from renewable energy sources. Communication from the Commission; COM (2005) 657 final; 2005.

Gilbert A., Reece G., Phylipsen D. An EU ETS Cap for France in Line with the emissions trading directive; ECOFYS, April 2006.

Madlener R, Kumbaroğlu G, Ediger V S. Modeling Technology Adoption as an Irreversible Investment Under Uncertainty: The Case of the Turkish Electricity Supply Industry. *Energy Economics*, 2005; 27(1); 139-163.

Menanteau P, Finon D, Lamy M-L. Prices versus quantities: choosing policies for promoting the development of renewable energy. *Energy Policy*, 2003; 31 (8); 799-812.

Mitchell C, Bauknecht D, Connor PM. Effectiveness through risk reduction: a comparison of the renewable obligation in England and Wales and the feed-in system in Germany. *Energy Policy*, 2006; 34; 297.305.

Reinaud J. Emissions trading and its possible impacts on investment decisions in the power sector. *IEA Information Paper*; 2003.

RTE. Bilan prévisionnel de l'équilibre offre-demande d'électricité en France; 2007.

RTE. Actualisation du bilan prévisionnel de l'équilibre offre-demande d'électricité en France à l'horizon 2013; 2008.

5. APPENDIX

5.1. Schedule of Investment

5.1.1. Schedule of Investment when there is Not Any Environmental Policy

State	e1		e4	
(in MW)	CCGT	GT	CCGT	GT
2011			129	
2012			1129	
2013	623		1067	
2015		930		1134
2016		940		1150
2017		950		1161
2018		961		1174
Total	**623**	**3781**	**2325**	**4619**

5.1.2. Schedule of Investment under Quota Policy

For all states, 1 MW is invested in CCGT in 2007.

	e1					e2			
(in MW)	NPP	SCHP	CCGT	WIND	GT	NPP	SCHP	CCGT	GT
2008	2688		1			937		1	
2009	2171		1			1880		1	
2010	1809		1			1515		1	
2011	1553		1			589		1	
2012	602	641	1					1	
2013			1					1	
2014			1					1	
2015			1					1	
2016			1				652	1	
2017		762					1054		
2018		597			8		294		
2019				2000					2000
Total	8823	2000	9	2000	8	4921	2000	9	2000

	e3					e4				
	NPP	SCHP	CCGT	WIND	GT	NPP	SCHP	CCGT	WIND	GT
2008	1235		1			2884		1		
2009	1326		1			2370		1		
2010	17		1			2012		1		
2011			1			1763		1		
2012			1			1596	1872	1		
2013			1			693		1		
2014			1					1		
2015			1					1		
2016		1029	1					1		
2017		867								
2018		105			8		128			
2019				2000					2000	8
Total	2578	2001	9	2000	8	11318	2000	9	2000	8

	e5		e6
	SCHP	CCGT	CCGT
2008		1	
2009		1	
2010		1	
2011		1	
2012		1	
2013		1	
2014		1	
2015		1	
2016		1	
2017	126		
2018	158		
Total	284	9	1

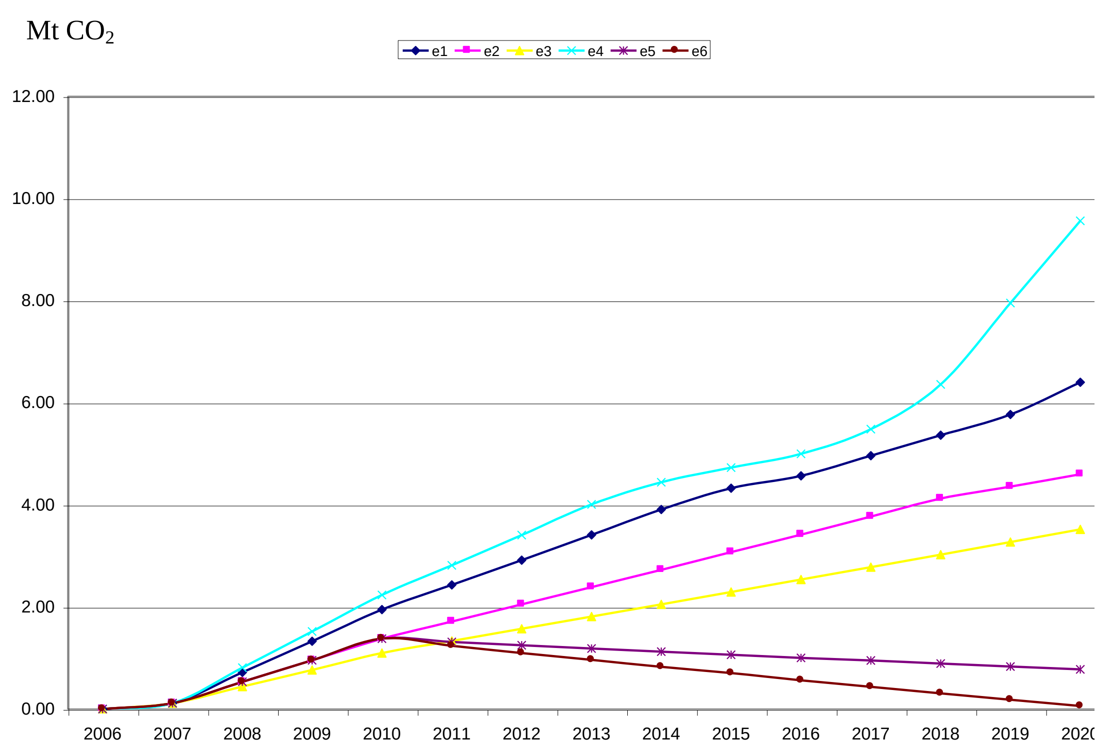
5.1.3. Schedule of Investment under Feed-in Tariff Policy

With a feed-in tariff policy, investments in windmills and solar PV stations are scheduled each year such to reach annual constraints on these technologies. It is the same for a policy combining quota and feed-in tariff, except in the two states of a high demand growth (e1 and e4). In these cases, other investments than windmills and solar PV plants are scheduled as shown below.

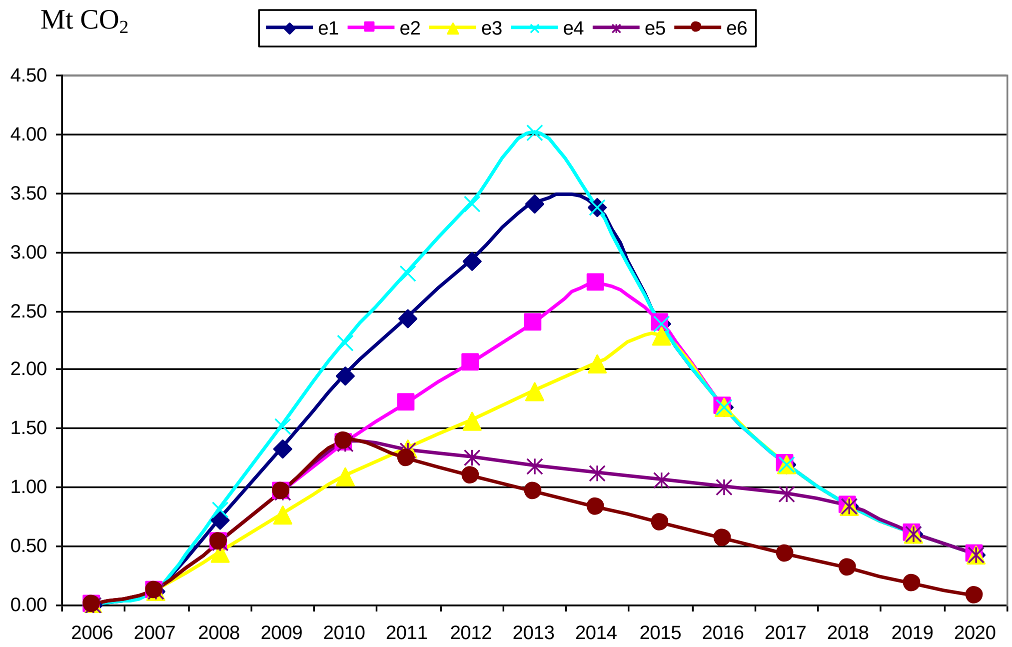
	e1				e4			
(in MW)	NPP	SCHP	CCGT	GT	NPP	SCHP	CCGT	GT
2008			1		1113		1	
2009	681		1		1422		1	
2010	262		1		901		1	
2011			1				1	
2012			1				1	
2013			1				1	
2014			1				1	
2015			1				1	
2016		665	1			246	1	
2017		775				976		
2018		570		8		778		8
Total	943	2010	9	8	3436	1754	9	8

5.2. Annual CO_2 Emissions

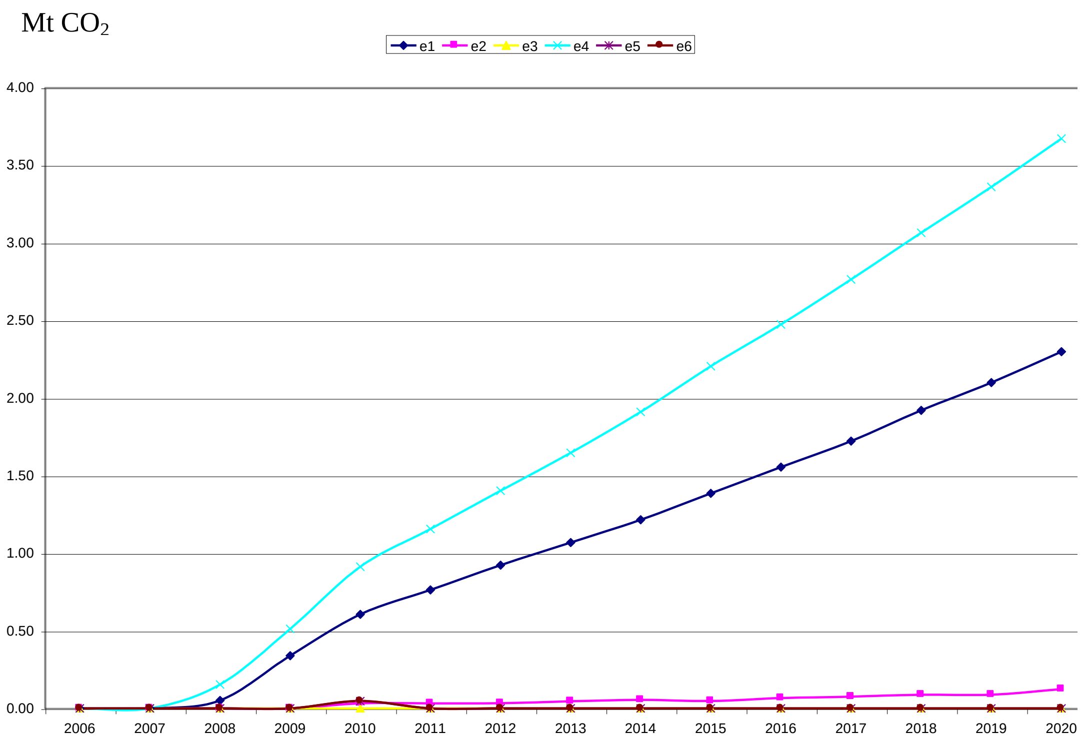
5.2.1. No Environmental Policy



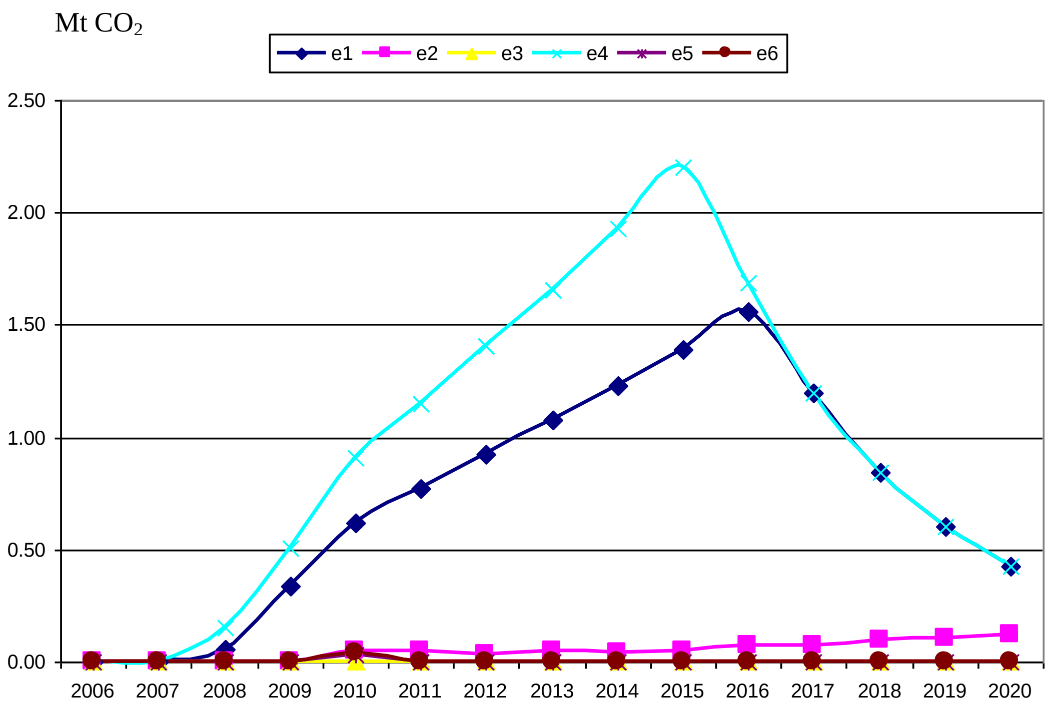
5.2.2. Quota Policy



5.2.3. Feed-in Tariff Policy



5.2.4. Feed-in Tariff and Quota Policy



FiME
LABORATOIRE COMMUN
DAUPHINE CREST EDF

Laboratoire de Finance des Marchés de l'Énergie

Institut de Finance de Dauphine, Université Paris-Dauphine
1 place du Maréchal de Lattre de Tassigny
75775 PARIS Cedex 16
www.fime-lab.org