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The choice of the regulated organization according to the investment in a marginal nuclear equipment

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Abstract: The French company, Electricité de France, produces nuclear baseload electricity in an European market which opens to competition. In this context, deciding to invest depends on the industrial structure controlled by the regulator: either as before a cost-plus regulated monopoly, or as possibly a pool in which the regulator obliges the cost price evolution to follow the generation long-term marginal cost which can be given by Combined-Cycle Gas Turbines. Under uncertainty, the firm delays its investment. But on pool it is not incited to overcapitalize: it is preferable to implement a pool rather than to maintain a monopoly.

Keywords: Deregulation; Irreversible investment; Real option; Cost price; Electricity

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1 Introduction

The context of the French electricity industry is modified: the country does not develop any more its electricity generation sector through Electricité de France (EdF), but it sets up a competition between independent power producers (IPPs) which will include this firm. This institutional change is characterized by the European electricity Directive of December 19th, 1996 which opens the production sector to competition by its articles 4, 5 and 6. We schematize it by the change of the sector organization from monopoly to pool. We approach the regulation aspect by its impact on the cost price variation rate. So the industrial structure modification is taken into account by four scenarios because the monopolistic cost-of-service regulation, in case of rate-of-return adjustment, can incite the firm to overcapitalize according to the Averch-Johnson effect. The organization of the disputable market which is then set up will be known only to the total sector opening in 2006. We envisage the emergence of an European pool which can however take two possible forms according to the British examples of the Electricity Pool of England and Wales, and since April 1st, 2001 of New Electricity Trading Arrangements (NETA).

This report of the industrial structure change coincidence with the question of the renewal of the nuclear power plants (NPPs) park foreseen by 2010, i.e. the end of life expectancy of the 900 and of 1300 MW NPPs, because the French production is 80% of nuclear origin. We want to know if the modification of the institutional context has an influence on the optimal decision of the firm's investment in a nuclear marginal project.

We define the generation sector by four scenarios of cost price evolution and the investment opportunity as being totally irreversible and expansible (section 2). These three characteristics of uncertainty, irreversibility and equipment timing flexibility allow to estimate the project opportunity value by means of the real options theory (cf. the surveys of Dixit and Pindyck, 1994; Trigeorgis, 1996). The opportunity is likened to a real option to defer, because the firm chooses to wait or to invest at any time. It consists of a call option. Under the various cases of regulation, we calculate the cost price from which it is optimal for the firm to invest, by distinguishing monopoly cases (section 3) from pool ones (section 4). Under uncertainty, the project is accepted if its value compensates for the waiting value of additional information about future market conditions, information given by the cost price. Real option adds this waiting value to the net present value (NPV): the opportunity value is estimated at the expanded net current value (ENPV; in: Trigeorgis, 1996). The NPV and ENPV rules define respectively the price thresholds of investment in scenario 1 and in three other scenarios. The ratio of the ENPV determined threshold to the NPV one puts in motto the option value multiple ϕ (cf. Dixit and Pindyck, 1994) the value of which is superior to 1 for this investment (section 5).

2 Hypotheses

2.1 Evolution of the industrial structure

"*Competition is favourable when it introduces new and useful products, widens markets, lowers production costs, replaces the less efficient producers by more efficient producers. Contrary to the fact that let understand the texts of the European Commission, which do not distinguish enough the various forms of competition, it can be harmful when it incites to install excess productive capacities or to renew them prematurely to prevent the entry of competitive firms. The temptation to break rules in work safety and legislation adds to these inefficiencies. Public utilities cannot be thus abandoned. Under a shape or another, public regulation is necessary*" (Henry, 1997).

In this network industry, EdF was an integrated monopoly which operated with increasing returns of scale. To avoid any abuse of dominant position, the authority in charge of the collective optimum, the State, submitted it to a cost-of-service regulation. This regulation illustrates the economic planning of production to which EdF was subjected from 1946 till 1996. EdF had to set up the French electricity network, the national monopoly being best to optimally manage the building of the production park (cf. Bergougnoux, 1987). So, the State forces[2] the firm to practise a cost price the constant decreasing evolution of which was beforehand fixed to answer to the baseload demand planning and to the objective of generation costs efficiency. Note that the optimal French park structure includes NPPs as baseload generation equipments, notably for reasons of national energy independence: that highlights this technological standardization implemented since 1974 by Messmer's government.

In a steady state, the rate-of-return of the monopolistic cost-of-service regulation is perfectly determined: the cost price evolution is certain. The determinist case (scenario 1) allows us to establish the investment threshold from the NPV rule. This benchmark is used to compare with investment thresholds under uncertainty, in the three following scenarios, deducted from the real options theory rule.

At the end of the electricity network development, the regulator does not know any more the long-term marginal cost with certainty. There is not a steady state: the cost price evolution is known only on average, and can undergo a downward jump further to the decreasing revision of rate-of-return by the regulator. By hypothesis, the regulation is imposed upon the firm which cannot intervene to influence the regulator's decision. We do not take into account the regulation period and suppose that the probability of this drop in tariff is definable over all this period (scenario 2).

Two concrete examples of pool are given by England and Wales with Pool, then NETA. In 1989 the Thatcher's privatization program wanted to avoid important modifications of quality

[2] This constraint allows us to admit the monopoly within the hypotheses framework of a price-taker.

and cost of service. The Pool functioning is regulated by an operator system, the Director General of Electricity Supply, which has to make sure that the unique Pool price reflects the marginal cost of the last NPP which is called on the basis of a bids system, i.e. in the merit order. By this physical balancing mechanism, the Imbalance Settlement, the price which decreases in trend is volatile (scenario 3).

The Pool dysfunctions appeared from 1992: it does not incite to the drop in cost price and involves a modification of the NPPs call order. In 1994 the regulator even imposed a price-cap on the Pool cost price. The Contracts for Difference allow to by-pass it (therefore the Pool represents only 20% of the transactions) by establishing contractual relations on the basis of a price which is negotiated except Pool between eligible customers and IPPs, whose equipments are almost exclusively constituted by Combined-Cycle Gas Turbines (CCGTs). To protect itself against the cost price fluctuations on the spot market, the firm can sell electricity on the basis of bilateral or multilateral contracts, concerning one or several exchanges. Since 2001 this contracts mechanism has been centralized under NETA, a contract market which consists of long-term contracts in 90% and short-term contracts in 8%. The Imbalance Settlement mechanism is maintained: the Balancing Mechanism manages 2% of the market. So the existence of this competitive market can favour the entry of a relatively reversible, little capital-intensive and easily funding technology, whose building delays are shorter. This CCGTs technology, dominant on the generation sector, determines the long-term marginal cost and then the evolution drift of cost price (scenario 4).

2.2 The firm's investment

The firm's environment is uncertain, the only source of uncertainty being the cost price p_t. The nuclear fuel and other inputs prices are supposed to be constant.

The envisaged specific capital is a baseload NPP, i.e. a completely irreversible and expansible equipment. It has a totally sunk cost: the firm cannot cut investment if the market conditions become unfavourable. The baseload NPP produces a constant quantity which we normalize to 1. The French nuclear technology is standardized and the uranium cost is constant: the production costs are normalized to 0. The technical standardization eliminates[3] any uncertainty on the initial capital cost K. We suppose that the life expectancy of this equipment is infinite and that its building is immediate. We note also that the capital cost benefits from economies of scale[4] and from positive externalities of a setup on the same site (cf. Lester and McCabe, 1993). Nevertheless we can admit that the regulator assures the optimality of the national generation park: it forces EdF to schedule its investment for a given number of NPPs and to group them together on sites. The incremental project does not modify the value of the firm's existing park. Furthermore because of the nuclear risks, the regulator controls strictly the respect for safety

[3] It is not the case of the American nuclear industry, that has to take into account an uncertain capital cost during the NPPs construction (cf. Pindyck, 1993).

[4] The costs of installed kW are cheaper for a 10 NPPs construction schedule than for a 4 NPPs one (cf. DIGEC, 1997, pp. 28 and 78).

standards by the firm which possesses such NPPs. This regulator does not either wish to see the property dispersal of these NPPs and the nuclear incremental equipment is an investment opportunity only for EdF. There is thus no strategic effect to be taken into account. Because CCGTs begin to compete with NPPs in baseload production, the effect of this technological competition is translated by a change of the cost price evolution. The capital expansion of the firm is thus total and the initial capital cost K remains constant.

Finally the regulator is always in charge to fulfil the Universal Service Obligations (USOs), but it is not the same any more for the investment policy which is within the firm's competence. The firm keeps the timing of this equipment the building of which is approved by the regulator.

The Modigliani-Miller theorem (1958) of separation of the investment and funding decisions is verified. The rational and risk-neutral firm maximizes the expected value of its project, i.e. the expected discounted value of the cash flow, equal according to our hypotheses to the cost price p_t, net of the initial capital cost K:

$$\max_{p_t} E\left\{(p_t - K)e^{-rt}; 0\right\}, \tag{1}$$

where r is the discount rate.

Its choice terms are either a discounted incremental value (if it invests), or 0 (if it waits):

$$\max_{p_t} V(p_t) = \{(1 - rdt)\, V(p_t) + E[dV]; 0\}. \tag{2}$$

In complete market, i.e. under the hypothesis of arbitrage opportunity absence (necessary for the option evaluation), it cannot realize any surplus, what expresses the Bellman equation:

$$rV(p_t)dt = E[dV] = dV. \tag{3}$$

3 Monopoly cases: the controlled evolution of the tariff

3.1 The determinist case: the "now or never" rule

In scenario 1, the certain price evolution follows the decreasing long-term marginal cost:

$$\frac{dp}{p_t} = \bar{\mu} dt \Longleftrightarrow p_t = p_0 e^{\bar{\mu} t},$$

where

$\bar{\mu}$ is the price evolution drift, $\bar{\mu} \leqslant 0$;

p_0 is the initial cost price.

In that determinist case, the investment rule answers a "now or never" strategy. The determination of the investment threshold means to decide to accept the project at the optimal time t^* ("now" strategy). If at this optimal time t^* the investment is not accepted, the option disappears: it is not possible to wait ("never" strategy). It is then equivalent to use the NPV rule (cf. Dixit, 1992).

The firm decides to exercise or not its option to maximize the expected value (1):

$$V(p_t) = \max_{p_t} E\left[(p_t - K)e^{-rt}\right] = \max_{p_t} E\left[(p_0 e^{\bar{\mu}t} - K)e^{-rt}\right].$$

There is always an optimal time to invest whatever the drift and the interest rate, because $\lim_{t\to\infty} e^{\bar{\mu}-rt} = 0$ (cf. McDonald and Siegel, 1986): investing is a better policy than waiting.

The price drift is not positive, i.e. $\bar{\mu} \leqslant 0$, and the cash flow generated by the investment project p_t is either constant or decreasing according to the time of service. The investment rule is then a "now or never" rule at time $t^* = 0$: it is optimal to invest immediately if $p_0 > p^*_{NPV} = K$, otherwise it is never optimal to invest. The rule is so expressed as:

$$\max\{p_0 - K; 0\}. \tag{4}$$

The decision to accept or to refuse the project is taken at $t^* = 0$. The investment is always accepted for $p_0 > p^*_{NPV} = K$. The firm's value $V(p_0)$ is maximum at the optimal decision-taking time $t^* = 0$. If $p_0 \leqslant K$, it is not optimal for the firm to invest. As the firm follows a "now or never" strategy, the firm cannot keep the option and wait to invest. The option disappears and the firm's value remains unchanged and be worthless as we normalized it. The NPP value depends on the investment rule:

$$V(p_0) = \begin{cases} 0 \text{ if } p_0 \leqslant p^*_{NPV} = K; \\ p_0 - K \text{ if } p_0 > p^*_{NPV}. \end{cases}$$

Proposition 1 *In the steady-state case of a cost-of-service regulation, the investment threshold is determined by the NPV rule: it is equal to the initial capital cost.*

The NPV rule is questioned under uncertainty: "the appeal to the classic criterion leads to investments, which are considered optimal *ex–ante* and which turn out excessive *ex–post*" (cf. Smeers, 1997, p. 679).

3.2 The case of the cost price jump: the ad nutum action of the regulator

In a cost-plus regulation with adaptation of the rate of return (scenario 2), the cost price can jump downwards further to an event: the regulator's intervention to decrease the rate. The firm anticipates this regulator's action only like a completely erratic intervention. The stochastic process of the cost price combines a Poisson process in the geometric Brownian motion:

$$\frac{dp}{p_t} = \bar{\mu}dt - dq,$$

where

q follows a Poisson process of which the increment is $dq = \begin{cases} 0 \text{ with probability } (1 - \psi dt) \\ \varphi \text{ with probability } \psi dt \end{cases}$

q can be interpreted as a firm's anticipation function of the regulator's intervention;

ψ is the average rate of this intervention occurrence;

φ is the decreasing percentage of the cost price in case of Poisson event, $0 < \varphi < 1$;

$\bar{\mu}$ is the decreasing process drift, $\bar{\mu}$ 6 0.

The risk-neutral rational firm maximizes its value (2), i.e. solves the Bellman equation (3) which can be written according to the Itô's lemma:

$$\bar{\mu} p_t V_p(p_t) - (\psi + r) V(p_t) + \psi V[(1-\varphi)p_t] = 0,$$

an ordinary differential equation (ODE). The ODE solution expresses the firm's value:

$$V(p_t) = A p_t^{\beta},$$

where the constant β is equal to:

$$\beta = -\frac{\bar{\mu} W\left(\frac{\ln(1-\varphi)\psi e^{\frac{(\psi+r)\ln(1-\varphi)}{\bar{\mu}}}}{\bar{\mu}}\right) - (\psi + r)\ln(1-\varphi)}{\bar{\mu}\ln(1-\varphi)}.$$

Call $W\left(\frac{\ln(1-\varphi)\psi e^{\frac{(\psi+r)\ln(1-\varphi)}{\bar{\mu}}}}{\bar{\mu}}\right) = W(w)$, where $w > 0$ because $\bar{\mu}$ 6 0; $(\varphi, \psi) \in [0;1] \times [0;1]$ and $r > 0$. $W(.)$ is a Lambert function defined as the inverse function of $x \mapsto xe^x$. The main real branch is increasing at decreasing rate in the positive scope: $W(0) = 0$ and $W_x(x) > 0$ for $x > 0$.

Note that $\beta < 0$ for $r > 0$.

¥ Proof: $r = 0$ is a root of β and β is decreasing with r because:
$\frac{\partial \beta}{\partial r} = \frac{\ln(1-\varphi) - \frac{\ln(1-\varphi)W(w)}{1+W(w)}}{\bar{\mu}\ln(1-\varphi)} = \frac{1}{\bar{\mu}[1+W(w)]} < 0.$

Now $V(p_t)$ has to verify the initial condition $V(0) = 0$ which determines the stopping region: when the cost price is zero, the project is worthless. We can deduct that $A = 0$, i.e. that it is never optimal for the firm to invest.

Proposition 2 *In the non steady-state case of a the cost-of-service rule, the firm is submitted to the decreasing cost price evolution and to the random downwards adaptation of this price. It is never optimal for the firm to invest under this regulation.*

Tariffs are supposed to be modified only at the beginning of the regulation period and not, as it is the case in reality, at any time during this period. The firm does not intervene either to decide with the regulator of the drop in tariff.

Uncertainty becomes too important so that the firm invests: the price threshold of investment gets to be infinite. In that case if the firm invests, it does not manage an optimal investment policy because it over-capitalizes. We thus can highlight the Averch-Johnson effect.

4 Pool cases: the competition incites the firm to base its price on the long-term marginal cost

4.1 The cost price fluctuates as the marginal cost and follows a geometric Brownian motion

The random evolution of the cost price is based on the long-term marginal cost of production and reflects the competition on the pool (scenario 3). The variation rate of the cost price follows a geometric Brownian motion:

$$\frac{dp}{p_t} = \bar{\mu} dt + \sigma dz,$$

where

the constant drift of this process ($\bar{\mu} \leqslant 0$) is thus such as $\bar{\mu} < r$: the McDonald and Siegel condition (1986) is verified;

the constant volatility σ represents the risk of the firm's activity, $\sigma > 0$;

z_t is a standard Wiener process.

The rational firm always wants to maximize its value by solving the program (2), i.e. the Bellman equation (3). According to the Itô's lemma, we obtain the ODE:

$$\frac{1}{2}\sigma^2 p_t^2 V_{pp}(p_t) + \bar{\mu} p_t V_p(p_t) - rV(p_t) = 0.$$

The shape of this ODE solution is[5]: $V(p_t) = Ap_t^{\beta_P}$ because it has to verify the initial condition $V(0) = 0$ which expresses that a zero price involves a zero firm's value, i.e. that it is not optimal for the firm to invest.

The value-matching condition means that at the investment time, the firm just receives the net cash-flow of the project:

$$V(p^*) = p^* - K.$$

The smooth-pasting condition is a technical derivation condition (the universe is convex: $V_p(p^*) > 0$) which guarantees the continuity between the firm's value and the exercised option value:

$$V_p(p^*) = 1.$$

From these two conditions we can deduct the price threshold:

$$p^* = \frac{\beta_P}{\beta_P - 1} K = \phi K.$$

[5] The positive root $\beta_P = \frac{1}{2} - \frac{\bar{\mu}}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\bar{\mu}}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}$.

It is optimal for the firm to wait when the cost price is lower than the price threshold of investment. It invests as soon as the price is superior to the price threshold p^*.

At any time t, its value is function of its decision to invest or to wait:

$$V(p_t) = \begin{cases} 0 \text{ if } p_t \leqslant p^* = \phi K, \\ \frac{1}{\beta_P} p_t \text{ if } p_t > p^*. \end{cases}$$

Proposition 3 (Dixit-Pindyck, 1994) *For an log-linear cost price evolution on pool, the firm invests later than the monopoly which produces in a steady state.*

4.1.1 The cost price fluctuates around the marginal cost according to a mean-reverting process or an Ornstein-Uhlenbeck process

Since 1989 CCGTs have represented 80% of the IPPs' investments. CCGTs have not practically any economic risk because they are covered by contracts. They supply the peak demand and become competitive in baseload generation: this technology dominates the electricity generation sector (scenario 4). The pool cost price follows a mean-reverting process, i.e. an Ornstein-Uhlenbeck process, where the mean is given by the long-term marginal cost of CCGTs:

$$dp = \eta(\bar{p} - p_t)dt + \sigma dz, \tag{5}$$

where

$\bar{p}$ is the long-term trend which follows the long-term marginal generation cost of CCGTs: it is the steady state towards which the generation sector goes;

η is the price convergence speed towards its long-term drift ($\eta > 0$), i.e. the speed of CCGTs' entry to the generation sector;

σ is the constant market volatility ($\sigma > 0$);

z_t is the standard Wiener process.

i) Competition in baseload generation: the long-term contracts under NETA - The cost price fixed by these contracts is certain: the volatility is equal to zero, $\sigma = 0$, and its evolution (5) becomes determinist. At any time t, the current price p_t is known according to the initial price p_0 and the CCGTs price $\bar{p}$:

$$\frac{dp}{dt} = \eta(\bar{p} - p_t) \Longleftrightarrow \frac{dp}{dt} + \eta p_t = \eta \bar{p} \Longleftrightarrow p_t = (p_0 - \bar{p})e^{-\eta t} + \bar{p}.$$

The firm chooses to invest to maximize its expected value (3):

$$V(p_t) = \max_{p_t} E\left[\left((p_0 - \bar{p})e^{-\eta t} + \bar{p} - K\right)e^{-rt}\right]. \tag{6}$$

Investing is always a better policy than waiting (cf. McDonald and Siegel, 1986): $\lim_{t \to \infty} \left[(p_0 - \bar{p})e^{-(\eta + r)t} + (\bar{p} - K)e^{-rt}\right] = 0, \forall (\eta, r) \in \mathbb{R}_+^* \times \mathbb{R}_+.$

It is necessary to distinguish a case of decreasing or constant cost price evolution and a case of increasing evolution of this price. That means to compare the long-term marginal costs of CCGTs and of NPPs, i.e. to establish the competitiveness of both equipments types. A decreasing interest rate is more favourable to NPPs, the more capital-intensive investment, but we suppose here that it is constant. This comparison thus depends on the gas price described by two scenarios: "high" and "low", because 70% of the long-term cost of CCGTs is due to the fuel cost (cf. DIGEC, 1997).

- **CCGTs competitiveness:** This competitiveness refers to the superiority of the NPPs long-term marginal cost to the CCGTs one. This case is possible for a "low" gas price scenario and illustrates the beginning of the CCGTs competition in baseload generation. The cost price evolution drift is not positive: $p_0 > \bar{p}$.

In that determinist case, the "now or never" investment rule at the initial time $t^* = 0$ is expressed as (4):

$$\max \{p_0 - K; 0\}.$$

It is optimal to invest immediately only if $p_0 > K$. Otherwise it is optimal to never invest if $p_0 \leqslant K$.

- **Nuclear competitiveness:** Under the "high" gas price scenario, the NPPs long-term marginal cost is lower than the CCGTs one. The drift is positive, i.e. $p_0 < \bar{p}$.

There is an option maturity time such as $V(p_{t^*}) > 0$ whatever is the sign of $(p_0 - K)$:

$$t^* = \max \left\{ \frac{1}{\eta} \ln \left[-\frac{(\eta + r)(p_0 - \bar{p})}{r(\bar{p} - K)} \right]; 0 \right\}.$$

¥ Proof: we deduct t^* from a necessary and sufficient condition to solve (6):
$\frac{\partial V(p_t)}{\partial t} = -(\eta + r) \left(p_0 - \bar{p} \right) e^{-(\eta - r)t} - r \left(\bar{p} - K \right) e^{-rt} = 0.$

The investment follows the same rule as in the monopoly case, i.e. it is only optimal to invest if $p_0 > K$. But it is also determined according to a threshold expressed from the steady-state threshold $\bar{p}$:

$$p^* = \frac{\eta \bar{p} + rK}{\eta + r} > K \text{ for } \bar{p} > K.$$

The investment rule results from a "now or never" strategy, which is coherent with the determinist evolution property of the contracts prices:

- if $p_0 > p^*$, the firm decide to invest at once;
- otherwise if $K < p_0 < p^*$ and $K < \bar{p}$, the investment is delayed for a later time $t^* > 0$ beyond which it is not optimal any more to invest because the capital cost decreases less quickly (of a factor e^{-rt}) than the cash-flow (of a factor $e^{-(\eta + r)t}$) in discounted terms.

The project is accepted only for $p_0 > K$. The firm's optimal value $V(p_t)$ depends on the optimal decision-making time t^*:

$$V(p_t) = \begin{cases} 0 \text{ if } p_0 < K; \\ p_0 - K \text{ if } p_0 > \bar{p} > K \ (t^* = 0); \\ \frac{\eta}{\eta+r}(\bar{p} - K)\left[\frac{r(\bar{p}-K)}{(\eta+r)(\bar{p}-p_0)}\right]^{r\frac{1}{\eta}} \text{ if } K < p_0 < p^* = \frac{\eta\bar{p}+rK}{\eta+r} < \bar{p} \\ \qquad (t^* = \frac{1}{\eta}\ln\left[\frac{(\eta+r)(p_0-\bar{p})}{r(\bar{p}-K)}\right] > 0); \\ p_0 - K \text{ if } K \leqslant p^* = \frac{\eta\bar{p}+rK}{\eta+r} \leqslant p_0 < \bar{p} \ (t^* = 0). \end{cases}$$

Proposition 4 *a. If the gas price is in accordance with a "low" price scenario ($p_0 > \bar{p}$), CCGTs are competitive in baseload generation. The firm invests in a NPP according to the NPV rule and independently of the CCGTs long-term marginal cost.*

b. The nuclear is competitive in baseload generation for a "high" gas price scenario ($p_0 < \bar{p}$). The firm invests for an initial price superior to the capital cost according to the NPV rule. This investment is immediately made if this price is superior to a price threshold $p^* = \frac{\eta\bar{p}+rK}{\eta+r}$, which depends of the CCGTs long-term marginal cost. Otherwise it is delayed at an optimal later time.

ii) Competition on pool - The cost price is a random variable ($\sigma \neq 0$ in (5)) and moves with reference to the CCGTs marginal cost. This long-term cost is a superior border price on the spot market but also for the short-term contracts under NETA, CCGTs becoming baseload generation equipments.

The firm makes the decision which verifies the Bellman equation (3), i.e. it solves the ODE:

$$\frac{1}{2}\sigma^2 V_{pp}(p_t) + \eta(\bar{p} - p)V_p(p_t) - rV(p_t) = 0, \quad (7)$$

whose solution has the following shape: $V(p_t) = Ap_t^{\beta} f(p_t)$. We deduct from the initial condition $V(0) = 0$ that only the positive value of β can be considered: $\beta = 1$.

In order to obtain a closed-form solution, we fix η, the speed of the CCGTs' entry to the generation sector, according to the market volatility σ and the competitiveness of this technology, established from the long-term drift $\bar{p}$:

$$\eta = \frac{\sigma^2}{2\bar{p}}.$$

Finally for $p \leqslant \frac{\sigma^2}{2\eta} \equiv \bar{p}$, the ODE solution is equal to (cf. Appendix A):

$$V(p_t) = Ap_t F(1, 3; \frac{2\eta}{\sigma^2}p_t),$$

where $F(.)$ is a Kummer equation the solution of which is the convergent hypergeometric series.

The boundary conditions, value-matching and smooth-pasting conditions, are respectively equal to:

$$V(p^*) = Ap^* F(1, 3; \frac{2\eta}{\sigma^2}p^*) = p^* - K \quad (8)$$

(the firm only receives the NPP value by investing) and to:

$$V_p(p^*) = Ap^* F_p(1, 3; \frac{2\eta}{\sigma^2} p^*) + AF(1, 3; \frac{2\eta}{\sigma^2} p^*) = 1 \quad (9)$$

(which is a technical condition of convex environment).

Thus, for $\bar{p} = \frac{\sigma^2}{2\eta}$, the optimal threshold is equal to (cf. Appendix B):

$$p^* = \sqrt{\bar{p}K} < \bar{p}.$$

This investment threshold is lower than the superior border of the cost price fixed by CCGTs. Beyond this threshold, the firm realizes the project, otherwise it waits for additional information about the future.

The value of the nuclear equipment is determined by the investment rule:

$$V(p_t) = \begin{cases} 0 \text{ if } p_t \leqslant p^* \equiv \sqrt{\bar{p}K} : \bar{p} > p^* > K; \\ \left(-\sigma^2 \frac{K}{p^*} + \sigma^2 + \eta K\right) p_t F(1, 3; \frac{2\eta}{\sigma^2} p_t) \text{ if } \bar{p} > p_t > p^*. \end{cases}$$

Proposition 5 *If GCCT is the most common peak-load equipment, its trend is defined as the superior border of the cost price* $\bar{p}$*. The firm implements the nuclear project from a price threshold* $p^* = \sqrt{\bar{p}K}$ *determined according to this border, even if the former threshold remains lower than the latter.*

It is however necessary to qualify our comment and to note that the nuclear technology has an option value (see, e.g., Epaulard and Gallon, 2001). The nuclear mastery which allows its standardization is due to a 600 "reactors-years" accumulated experiment. Stopping the nuclear program led to reduce the energy choice terms in the future. The question settles in terms of the CCGTs competitiveness, the gas price being random, and in terms of energy independence.

5 Concluding remarks

We compare the cost price thresholds of the various scenarios to that one of scenario 1, i.e. the monopoly case under certainty. This price threshold is determined by the NPV rule and it is equal to the initial capital cost: $p^*_{VAN} = K$. Under uncertain scenarios, the investment threshold p^* is superior to this initial capital cost:

$$p^* = \phi p^*_{VAN}, \text{ with the option value multiple } \phi > 1.$$

We confirm the result of McDonald and Siegel (1986); Dixit and Pindyck (1994) for the various scenarios which we built to report institutional changes. The firm invests when the future return on the project is equal to the capital cost. Under uncertainty, this return has to compensate for the value of information about the future cost price. The firm prefers to be flexible and to decide its investment timing according to the collected information.

On pool, the value of ϕ can depend on the drift $\bar{\mu}$ and on the volatility σ of the firm's activity (scenario 3) while it can depend on the CCGTs cost price $\bar{p}$, the speed of the CCGTs' entry η to the generation sector being fixed with regard to σ (scenario 4). The investment threshold p^* increases with the volatility σ, measure of the competition degree in the sector. The increase of uncertainty lowers all the less investment as the firm is in a competitive structure. Ultimately uncertainty has no more influence on investment: a firm in pure and perfect competition cannot put back an investment project because otherwise the opportunity to invest would be exercised by a competitor. Uncertainty has a twice as important effect for a firm among which the market power, measured by the difference between the cost price and the generation marginal cost, is superior to the average market power (see, e.g., Guiso and Parigi, 1996). The strategic effect lowers the value of ϕ. Now, the electricity industry remaining subjected to the USOs, the effect of the market power is partially thwarted by the market regulation, even totally in the NPPs case which we envisaged.

6 Appendix

6.1 Appendix A: the ODE solution $V(p) = ApF\left(1,3;\frac{2\eta}{\sigma^2}p\right)$

To simplify we do not write any time index of variables. The firm has to solve the ODE (7):

$$\frac{1}{2}\sigma^2 V_{pp} + \eta(\bar{p} - p)V_p - rV = 0.$$

This ODE solution is equal to: $V(p) = Ap^{\beta}f(p)$, where A and β are two constants such as $f(p)$ is an ODE solution.

Write the partial derivatives:

$$\begin{cases} V_{pp} = Ap^{\beta}f_{pp} + 2A\beta p^{\beta-1}f_p + A\beta(\beta-1)p^{\beta-2}f \\ V_p = Ap^{\beta}f_p + A\beta p^{\beta-1}f \end{cases}$$

By simplifying by A, the equation (7) becomes:

$$p^{\beta}\left[\frac{1}{2}\sigma^2 f_{pp} + \eta(\bar{p}-p)f_p - (\eta\beta + r)f\right] + p^{\beta-1}\left[\sigma^2\beta f_p + \eta\bar{p}\beta f\right] + p^{\beta-2}\left[\frac{1}{2}\sigma^2\beta(\beta-1)\right] = 0$$

and involves:

$$\begin{cases} \frac{1}{2}\sigma^2 f_{pp} + \eta(\bar{p}-p)f_p - (\eta\beta + r)f = 0 \\ \sigma^2\beta f_p + \eta\beta\bar{p}f = 0 \\ \frac{1}{2}\sigma^2\beta(\beta-1) = 0 \end{cases} \tag{10}$$

We can deduct the value of β from the third equation (10): $\beta = 0$ or $\beta = 1$. From the boundary condition $V(0) = 0$, only the positive value of β is considered:

$$\beta = 1.$$

Thsu, the second equation (10) is equal to:

$$f_p = -\frac{\eta f}{\sigma^2}.$$

The first equation (10) becomes:

$$\frac{1}{2}\sigma^2 f_{pp} - \left[\frac{\eta^2}{\sigma^2}(\bar{p} - p) + \eta + r\right] f = 0.$$

Call $x = \frac{2\eta}{\sigma^2}p \Longleftrightarrow p = \frac{\sigma^2}{2\eta}x$. If $f(p) = g(x)$, we obtain the partial derivatives:

$$\begin{cases} f_p = \frac{\partial g(x)}{\partial x}\frac{\partial x}{\partial p} = g_x \frac{2\eta}{\sigma^2} \\ f_{pp} = \frac{\partial g_x(x)}{\partial x}\frac{\partial x}{\partial p} = g_{xx}\left(\frac{2\eta}{\sigma^2}\right)^2 \end{cases}$$

The first equation (10) is equal to:
$g_{xx}x\eta + g_x\left(\frac{2\eta}{\sigma^2}\right)\left[-\left(\frac{\sigma^2}{2}\right)x + \left(\sigma^2\beta + \eta\bar{p}\right)\right] - g\eta\beta = 0.$
By dividing by η:
$g_{xx}x + g_x\left[-x + \frac{2}{\sigma^2}\left(\sigma^2\beta + \eta\bar{p}\right)\right] - g\beta = 0.$
Call $B = \frac{2}{\sigma^2}\left(\sigma^2\beta + \eta\bar{p}\right) = 2\beta + \frac{2\eta}{\sigma^2}\bar{p}$, then:

$$g_{xx}x + g_x(-x + B) - g\beta = 0. \tag{11}$$

This equation (11) is a Kummer equation the solution of which is the convergent hypergeometric series (because the risk-free interest rate r is defined as the discount rate, then $B - \beta > 0$ and thus the series is convergent for $|x| \leqslant 1 \Longleftrightarrow \left|\frac{2\eta}{\sigma^2}p\right| \leqslant 1 \Longrightarrow 0 \leqslant p \leqslant \frac{\sigma^2}{2\eta}$):

$$F(\beta, B(\beta); x) = 1 + \frac{\beta}{B}x + \frac{\beta(\beta+1)}{B(B+1)}\frac{x^2}{2!} + \frac{\beta(\beta+1)(\beta+2)}{B(B+1)(B+2)}\frac{x^3}{3!} + \ldots$$

Finally we obtain the ODE solution $V(p) = Ap^\beta f(p)$:

$$V(p) = Ap^\beta F(\beta, B; \frac{2\eta}{\sigma^2}p).$$

Because $\beta = 1$ and $B = 2 + \frac{2\eta}{\sigma^2}\bar{p}$, the ODE solution is equal to:

$$V(p) = ApF(1, 2 + \frac{2\eta}{\sigma^2}\bar{p}; \frac{2\eta}{\sigma^2}p).$$

The value-matching and smooth-pasting conditions would allow us to find the constant A, but only a numeric solution is possible because the hypergeometric series has an infinity of terms. To explicit a threshold, we are going to take the simplest numeric example:

$$B = 3 \Longrightarrow \frac{2\eta\bar{p}}{\sigma^2} = 1 \Longrightarrow \bar{p} = \frac{\sigma^2}{2\eta}.$$

$\bar{p}$ is superior border of the cost price p_t: $0 \leqslant p_t \leqslant \frac{\sigma^2}{2\eta} \equiv \bar{p}$. The speed of the CCGTs' entry η on the generation sector is fixed according to the market volatility σ and to this technology competitiveness expressed as the long-term drift $\bar{p}$.

Thus, the ODE solution is expressed as:

$$\boxed{V(p) = ApF(1, 3; \frac{2\eta}{\sigma^2}p)}$$

6.2 Appendix B: the price threshold p^*

• Determination of the price threshold p^*:

Express: $F(1,3;x) = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ... = 1 + 2!\left[\frac{x^2}{3!} + \frac{x^3}{4!} + ...\right] = 1 + \frac{2!}{x^2}\left[\frac{x^3}{3!} + \frac{x^4}{4!} + ...\right]$

$\Longrightarrow F(1,3;x) = 1 + \frac{2}{x^2}\left[e^x - 1 - x - \frac{x^2}{2}\right] = \frac{2}{x^2}\left[e^x - 1 - x\right]$.

The Kummer function verifying the boundary conditions is equal to:

$F(1,3;\frac{2\eta}{\sigma^2}p^*) = 1 + \frac{2}{\left(\frac{2\eta}{\sigma^2}p^*\right)^2}\left[e^{\frac{2\eta}{\sigma^2}p^*} - 1 - \frac{2\eta}{\sigma^2}p^* - \frac{\left(\frac{2\eta}{\sigma^2}p^*\right)^2}{2}\right] = \frac{\sigma^2}{2\eta^2 {p^*}^2}\left[e^{\frac{2\eta}{\sigma^2}p^*} - 1 - \frac{2\eta}{\sigma^2}p^*\right]$.

We derive this equation to obtain:

$F_p(1,3;\frac{2\eta}{\sigma^2}p^*) = -\frac{\sigma^2}{\eta^2 {p^*}^3}\left[e^{\frac{2\eta}{\sigma^2}p^*} - 1 - \frac{2\eta}{\sigma^2}p^*\right] + \frac{\sigma^2}{2\eta^2 {p^*}^2}\left[\frac{2\eta}{\sigma^2}e^{\frac{2\eta}{\sigma^2}p^*} - \frac{2\eta}{\sigma^2}\right]$

$\Longrightarrow F_p(1,3;\frac{2\eta}{\sigma^2}p^*) = -\frac{2}{p^*}F(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{1}{\eta {p^*}^2}\left[e^{\frac{2\eta}{\sigma^2}p^*} - 1\right]$

$\Longrightarrow F_p(1,3;\frac{2\eta}{\sigma^2}p^*) = -\frac{2}{p^*}F(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{1}{\eta {p^*}^2}\frac{2\eta\sigma^2}{2\eta\sigma^2}\left[e^{\frac{2\eta}{\sigma^2}p^*} - 1 - \frac{2\eta}{\sigma^2}p^* + \frac{2\eta}{\sigma^2}p^*\right]$

$\Longrightarrow F_p(1,3;\frac{2\eta}{\sigma^2}p^*) = -\frac{2}{p^*}F(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{2\eta}{\sigma^2}F(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{2}{\sigma^2 p^*}$

$\Longrightarrow Ap^*F_p(1,3;\frac{2\eta}{\sigma^2}p^*) = -2AF(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{2A\eta}{\sigma^2}F(1,3;\frac{2\eta}{\sigma^2}p^*)p^* + \frac{2A}{\sigma^2}$

$\Longrightarrow Ap^*F_p(1,3;\frac{2\eta}{\sigma^2}p^*) + AF(1,3;\frac{2\eta}{\sigma^2}p^*) = -AF(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{2A\eta}{\sigma^2}F(1,3;\frac{2\eta}{\sigma^2}p^*)p^* + \frac{2A}{\sigma^2} = 1$ (cf. (9)).

By substituing $F(1,3;\frac{2\eta}{\sigma^2}p^*)$ by its value expressed in the value-matching condition (8):

$-\frac{p^*-K}{p^*} + \frac{2\eta}{\sigma^2}(p^* - K) + \frac{2A}{\sigma^2} = 1$

$\Longrightarrow \frac{2\eta}{\sigma^2}{p^*}^2 + \left(\frac{2A}{\sigma^2} - 2 - \frac{2\eta}{\sigma^2}K\right)p^* + K = 0$

$$\boxed{\frac{2\eta}{\sigma^2}{p^*}^2 + \left(\frac{2A}{\sigma^2} - 2 - \frac{2\eta}{\sigma^2}K\right)p^* + K = 0} \tag{12}$$

• Determination of the constant A:

To express the constant value A according to p^*, we are going to derive the smooth-pasting condition (9):

$F_{pp}(1,3;\frac{2\eta}{\sigma^2}p^*) = \frac{2}{{p^*}^2}F(1,3;\frac{2\eta}{\sigma^2}p^*) - \frac{2}{p^*}F_p(1,3;\frac{2\eta}{\sigma^2}p^*) + \frac{2\eta}{\sigma^2}F_p(1,3;\frac{2\eta}{\sigma^2}p^*) - \frac{2}{\sigma^2{p^*}^2}$.

Because $\frac{\partial}{\partial p}\left[Ap^*F(1,3;\frac{2\eta}{\sigma^2}p^*)\right] = Ap^*F_p(1,3;\frac{2\eta}{\sigma^2}p^*) + AF(1,3;\frac{2\eta}{\sigma^2}p^*) = 1$ (cf. (8)),

the second-order derivative is equal to 0:

$\frac{\partial^2}{\partial p^2}\left[Ap^*F(1,3;\frac{2\eta}{\sigma^2}p^*)\right] = Ap^*F_{pp}(1,3;\frac{2\eta}{\sigma^2}p^*) + 2AF_p(1,3;\frac{2\eta}{\sigma^2}p^*) = 0$

$\Longrightarrow Ap^*F_{pp}(1,3;\frac{2\eta}{\sigma^2}p^*) = A\frac{2}{p^*}F(1,3;\frac{2\eta}{\sigma^2}p^*) - 2AF_p(1,3;\frac{2\eta}{\sigma^2}p^*) + Ap^*\frac{2\eta}{\sigma^2}F_p(1,3;\frac{2\eta}{\sigma^2}p^*) - \frac{2A}{\sigma^2 p^*}$

$\Longrightarrow Ap^*F_{pp}(1,3;\frac{2\eta}{\sigma^2}p^*) + 2AF_p(1,3;\frac{2\eta}{\sigma^2}p^*) = \frac{2A}{p^*}F(1,3;\frac{2\eta}{\sigma^2}p^*) + Ap^*\frac{2\eta}{\sigma^2}F_p(1,3;\frac{2\eta}{\sigma^2}p^*) - \frac{2A}{\sigma^2 p^*} = 0$

$\Longrightarrow 2\frac{p^*-K}{{p^*}^2} + \frac{2\eta}{\sigma^2}\left(1 - AF(1,3;\frac{2\eta}{\sigma^2}p^*)\right) - \frac{2A}{\sigma^2 p^*} = 0$ (cf. (8))

$\Longrightarrow 2\frac{p^*-K}{{p^*}^2} + \frac{2\eta}{\sigma^2}\left(1 - \frac{p^*-K}{p^*}\right) - \frac{2A}{\sigma^2 p^*} = 0$

$\Longrightarrow A = \sigma^2 p^*\left[\frac{p^*-K}{{p^*}^2} + \frac{\eta}{\sigma^2}\left(1 - \frac{p^*-K}{p^*}\right)\right]$

$$\Longrightarrow A = \left[\sigma^2 - \sigma^2 \frac{K}{p^*} + \eta p^* - \eta p^* + \eta K\right]$$

$$\boxed{A = -\sigma^2 \frac{K}{p^*} + \sigma^2 + \eta K} \tag{13}$$

Subtitute (13) in (12) to obtain the price threshold p^*:

$$\boxed{p^* = \sqrt{\bar{p}K}}$$

References

[1] Bergougnoux, J., 1987, Les leçons de l'expérience du financement du programme électronucléaire français, in: G. Terny and R. Prud'homme eds , Le financement des équipements publics de demain, Chapter 8.

[2] DIGEC, 1997, Les "coûts de référence" en production électrique, Report under J. Batail's direction for Ministère de l'Economie, des Finances et de l'Industrie, Ministère de l'Industrie, DGMP, France.

[3] Dixit, A.K. and R.S. Pindyck, 1994, Investment under uncertainty (Princeton: Princeton University Press).

[4] Epaulard, A. and S Gallon, 2001, La valorisation du projet nucléaire EPR par la méthode des options réelles, Economie et Prévision 149, 3, 29-51.

[5] Henry, C., 1997, Concurrence et services publics dans l'Union Européenne, Revue de l'énergie 486, 187-198.

[6] Lester, R.K. and M.J. McCabe, 1993, The effect of industrial structure on learning by doing in nuclear plant power operation, RAND Journal of Economics 24, 3, 418-438.

[7] McDonald, R. and D. Siegel, 1986, The value of waiting to invest, The Quarterly Journal of Economics 101, 3, 707-727.

[8] Modigliani, F. and M.H. Miller, 1958, The cost of capital, corporation finance and the theory of investment, American Economic Review 48, 3, 261-297.

[9] Pindyck, R.S., 1993, Investments under uncertain cost, Journal of Financial Economics 34, 53-76.

[10] Smeers, Y., 1997, Evaluation des investissements électriques vers une évolution des méthodes, Revue de l'Energie 492, 674-682.

[11] Trigeorgis, L., 1996, Real options (Cambridge, Mass.: MIT Press).