Choice of nuclear power investments under price uncertainty: Valuing modularity

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Abstract: *We consider the choice problem faced by a firm in the electricity sector which holds two investment projects. The first project is an irreversible investment in a large nuclear power plant. The second project consists in building a flexible sequence of smaller, modular, nuclear power plants on the same site. In other words, we compare the benefit of the large power plant project coming from increasing returns to scale, to the benefit of the modular project due to its reduced risk (flexibility). We use the theory of real options to measure the value of the option to invest in the successive modules, under price uncertainty.*

From this theory, it is well-known that risk-neutral entrepreneurs will decide to invest only if the market price of electricity exceeds the cost of electricity by a positive margin which is an increasing function of the market risk. In particular, this margin is larger for the irreversible investment than for the modular project. This is because the investment process in the modular project can be interrupted at any time when the market conditions deteriorate, thereby limiting the potential loss of the investor.

We consider in particular an environment where the discount rate is 8% and volatility of the market price of electricity equals 20% per year. The modular project consists in four units of 300 MWe each, and in which 40% of the total overnight cost is borne by the first module. We show that the benefit of modularity is equivalent in terms of profitability to a reduction of the cost of electricity by one-thousand of a euro per kWh.

1. Introduction

Context

The opening up of electricity markets to competition will terminate the logic by which investments in electricity generation installations were planned based on long term demand forecast, that was prevalent during the second half of the twentieth century. In the future, investments by competitive producers will be controlled by the need for cost effectiveness in a risky universe, rather than the need to cover demand on a captive market.

The electricity generating companies environment has become more complex and riskier. With the old system, market security and price stability made it possible to reason in an environment in which the only uncertainties were fuel price and demand level. Liberalization of markets has increased sources of uncertainty. In particular, when making their investment choices, electricity producers face market risks (future demand, supply and prices) and legal risks (lack of visibility on the future legal environment controlling the electricity generation activity).

Furthermore, a planning error can have a much greater impact on a competitive company operating in a liberalized market than in a monopolistic situation. In the case of a monopoly, an unpredicted situation could be compensated by an increase in rates to match real costs, while in a competitive environment, the result would be a loss that would endanger the durability of the company, or at least reduce the cost effectiveness of a project. Finally, the increase in the proportion of private shareholdings in electricity companies increases the trend towards control or limitation of risks when making investment choices in liberalized markets.

The impact of liberalization of markets on investment choices in nuclear power

Since future investments in nuclear power generation capacity will be made within this new context, it is worth studying the impact of this modification on investments choices made by electricity producers. In particular, it is legitimate to wonder if electricity generators who will have chosen this production means will continue to prefer large capacity units as they did in the past, to optimize the benefit of the size effect and thus enjoy attractive production costs (Barré, 2001), or if the uncertainty related to the competitiveness of electricity markets will encourage them to choose smaller units to reduce the risk.

This article discusses how a producer faced with a predicted change in the competitive price of electricity will be able to compare a sequence of investments in medium capacity nuclear power plants (4 x 300 MWe) with an investment in a high capacity unit (1200 MWe). In other words, how to choose between the flexibility of the modular investment and the efficiency of the high capacity unit due to increase in economy of scale?

Intuitively, the solution offered by modular power plants would appear to be most suitable for a competitive environment with strong uncertainties about the supply and the price of electricity. Because of the irreversibility of the investment in the high capacity unit, it is optimal for the producer to invest only if the market price of electricity is high enough compared to the cost of electricity. The option of making sequential decisions when several medium sized nuclear modules are used, enables the producer to be more aggressive in its investment strategy by initiating the construction of the first unit at a smaller critical price of electricity. The purpose of this article is to present a model of investment choices to provide back up material for this intuition.

An investment choice model

This study is based on use of the real options theory. The net present value approach routinely used for the evaluation of an investment project cannot allow for the possibility of making sequential choices (delaying investments, abandoning the project) or taking account of the uncertainty about changes in the cost effectiveness of the project. The real options theory provides a means of eliminating these imperfections. This calculation method was initially proposed by Arrow and Fischer (1974) and Henry (1974), and considers investment expediency as an option that can be selected or abandoned over time within a procedure that takes account of the degree of irreversibility of sequential decisions. Gollier (2001) provides an overview of this literature.

In the case of a sequential investment, starting construction of the first module creates the option of investing in a second module, so that it will then become possible to consider uprating the installed capacity. Thus, the producer will have the opportunity to prolong his investment or to stop at the level reached, after the construction of each module.

In this model, the decision maker needs to decide between delaying his decision, or starting construction of a large unit, or starting construction of the first module of the modular power plant. If the price of electricity $P(t)$ is equal to the full cost θ per kWh of a production capacity, the arbitration to be made is between construction of the plant and delaying the decision. The choice is then between taking the risk of the price of electricity dropping and having started a non-cost effective investment, or delaying to wait until knowledge about price changes. The model thus aims to clarify the investor's choice and to define the price threshold P^* starting from which it is economically effective to invest in a power plant being studied.

As a first approximation, we assume pure and perfect competition on the electricity market. The investment does not have any effect on the price of electricity, defined exogenically by a trend and a standard deviation. Moreover, the decision to invest has no consequence on the investment strategy of competitors. Finally, we assume that the order of magnitude of discounted production costs for the high capacity unit are the same as for the unit composed of four 300 MWe modules, for the sole purpose of demonstrating application of the flexibility of a modular concept. The main difference between the two concepts is then the flexibility of the construction program.

2. Problem description

We will consider a competitive electricity market in which the price of electricity P, expressed in cents/kWh, varies randomly in time. The annual rate of the price increase is denoted α. The volatility of this price is measured by the standard deviation σ for this rate of increase. To be precise, the classical assumption that $dP(t)/P(t) = \alpha dt + \sigma dz(t)$ is made, in which $P(t)$ is the price at time t and $z(t)$ is a standard Brownian.

It is assumed that two nuclear technologies are available. One is "conventional", consisting of a large unit. The other is modular and corresponds to a series of medium-sized nuclear power installations. The number of potential series units is denoted n. Unit number i is characterized by a discounted average cost per kWh equal to θ_i, its construction time T_i and its life L_i expressed in years. Investments are made in sequence, in the sense that construction of unit $i+1$ cannot be decided upon until construction of unit i is terminated.

It is assumed that the company and its shareholders are neutral towards the risk. The discount rate is equal to r (expressed in % per year). In this environment, the investment decision depends on the sign of the net present value (NPV) of the expected cash flows generated by this investment. The sequential nature of the investment process combined with construction times introduces a great deal of complexity in the cost-benefit analysis of the project. The decision to invest in the construction of series unit i must take account of the NPV of flows generated by the unit, and also the value of the option to invest in unit i+1 that becomes possible with this decision. This value can be calculated using the real options theory, as described in a summary by Dixit and Pindyck (1994).

In the remainder of this presentation, we propose to determine the optimum timing of the investment in the different series units and the market value of the project as a whole, as a function of the current price of electricity and technical characteristics of the project. Any dynamic problem of this type must be planned anticipating optimum future decisions as a function of random changes in the price per kWh. Therefore, the problem has to be solved by reverse induction. We will begin by assuming that $n-1$ units have already been built, and we will study the decision to invest in the last unit. This question is studied in the following section. Section 5 proposes a plausible numerical solution to this problem.

3. Analysis of the decision to invest in the last series unit

Assume that $n-1$ units have already been built. The utility company would like to determine the optimum time at which to build the last unit. Figure 1 shows the sequence of cash flows that would be generated. If the decision to build this last unit is taken on date t, production and sale of a constant flow of K_n kWh start immediately after construction of the unit is terminated at $t+T_n$, and continue until shutdown of the unit at $t+T_n+L_n$. At any time τ during this production period, the utility company collects a regular income of $K_n P(\tau)$ and pays an outgoing cost flow equal to $K_n\theta_n$, to integrate all installation, maintenance and fuel costs. It is assumed that these variable costs are low enough to be optimum to generate the electricity base production throughout the life of the installation. This assumption is acceptable for installations with a low marginal production cost operated in a market without any overcapacity of base production means.

The net present value per unit power of the cost flow of the last module is equal to

$$I_n = \int_{T_n}^{T_n+L_n} \theta_n e^{-r\tau} d\tau = e^{-rT_n} \frac{1-e^{-rL_n}}{r} \theta_n .$$

The cash flow due to the sale of the electricity at market price $P(\tau)$ throughout the life of the unit is random. Since the company is neutral to risk, all that is important is the expected net present value. It is written as follows, per unit power,

$$V_n(P) = E\left[\int_{T_n}^{T_n+L_n} P(\tau)e^{-r\tau}d\tau \middle| P(0) = P\right] = k_n P$$

where

$$k_n = e^{-(r-\alpha)T_n}\frac{1-e^{-(r-\alpha)L_n}}{r-\alpha}$$

where α is the predicted rate of increase of the price of electricity.

The company's problem consists of determining the optimum date *t* at which this investment should be made, so as to maximize the expectancy of the expected net present value $V_n(P(t))-I_n$. Let *P* be the current price per kWh. If the investment is made immediately, the expected NPV of the project is $V_n(P)-I_n$. Even if this value is positive, it is not necessarily the optimum time to invest. Delaying this decision to build this last unit has the advantage that it becomes possible to obtain further information about the future price. In particular, this can "rescue" the company if a sudden drop in price is observed. Therefore, the action of waiting has an "option value" in itself, that should be included in the cost-benefit analysis. Mathematically, the decision problem for the last unit is written as follows:

$$F_n(P) = \max_t E\left[e^{-rt}\left(k_n P(t) - I_n\right)\middle| P(0) = P\right] \quad (1)$$

$F_n(P)$ is equal to the expected net present value of flows generated by the last unit when the optimum investment strategy is followed. The problem (1) represents a conventional illustration of the theory of real options (in this case adapted to take account of construction times and the finite life of the unit). Appendix 1 explains briefly how this problem can be solved. In particular, it should be noted that the optimum investment strategy consists of making an investment if and only if the market price exceeds a given threshold P_n^*. Synthetically, the result is as follows:

$$F_n(P) = \begin{cases} A_n P^\beta & si\ P < P_n^* \\ k_n P - I_n & si\ P \geq P_n^* \end{cases} \quad (2)$$

where β is the largest root of the following quadratic equation

$$0.5\sigma^2\beta(\beta-1) + \alpha\beta - r = 0. \quad (3)$$

and in which the critical price threshold P_n^* satisfies the following equation:

$$P_n^* = \frac{\beta}{\beta-1}\frac{I_n}{k_n} \quad \text{et} \quad A_n = \frac{k_n}{\beta(P_n^*)^{\beta-1}}. \quad (4)$$

Since β is greater than 1, it can be seen that the critical price exceeds I_n, the net present value of the total costs of this last series unit per kWh. At the time of the decision to invest, the difference is the expected net present value of the profit flows, per useful kW. Thus, taking account of the uncertainty on price changes and irreversibility of the investment, it is not optimum to invest when the price is equal to the costs. It would be preferable for the investor to delay his investment and wait until the price is greater than his production costs.

4. Analysis of the decision to build the last but one series unit

In the previous section, we determined the optimum investment strategy in the last production module, assuming that the *n-1* other modules were already built. We can now attempt to determine the optimum investment strategy in the last but one module, assuming that the previous *n-2* modules have already been built. At this state of the development, it is important to realize that this investment includes the option to invest in the last series unit, in addition to the cash flows and expenses generated by this module. In section 3, we calculated the value $F_n (P)$ of this option regardless of the current price P per kWh.

Thus, taking account of the option available from this first investment makes it more difficult to determine the optimum investment strategy in this module *n-1*. As long as the option consisting of starting construction of the last but one unit has not been used, the global value of the project (denoted F_{n-1}) satisfies a rule similar to that for F_n, in other words:

$$F_{n-1}(P) = \max_t E\left[e^{-rt} \left(k_{n-1}P(t) - I_{n-1} + e^{-rT_{n-1}} E\left[F_n(P(t+T_{n-1}) \middle| P(t) \right] \right) \middle| P(0) = P \right], \qquad (5)$$

where k_{n-1} and I_{n-1} are defined in the same way as k_n and I_n in the previous section. Nevertheless, it should be noted that there is a fundamental difference. On the date on which the option to build the last but one module is analyzed, the net present value of the entire residual project takes account of cash flows for this unit n-1 and the value of the option to invest in the last unit which will become available in T_{n-1} years.

In fact, there is no analytic solution to this problem, and there are actually two technical problems. The first is non-linearity of F_n with P described in the previous section. The second problem is the difficulty of calculating the expected value of the option to build the last unit that will only be available T_{n-1} years after the decision to build the unit *n-1*. These two difficulties make it impossible to obtain an analytic solution to this problem. Appendix 2 briefly describes the procedure to determine P^*_{n-1}. A computer program was written to find a numerical solution for the values of $P^*_{n-1}, P^*_{n-2}, \ldots$ by reverse iteration. Obviously, it is still true that it is only optimum to invest in this module n-1 if the price of electricity exceeds a given threshold P^*_{n-1}.

We can proceed in the same manner by reverse induction to determine the critical price threshold for building the module before the last but one module, and so on back to the first unit. As we work forwards in the modular project, the number of options and the value of each option increases, which encourages the decision maker to accept a lower critical price threshold.

5. A numerical illustration

The discounted calculations in this illustration are made with a discount rate of 8%, which is an average value for OECD countries.

The objective is to compare two investment projects, one of which is a reactor with a capacity of 1200 MWe, and the second is a sequence of four modular reactors with a unit capacity of 300 MWe. The following table gives electricity production costs used for this reference example. These costs are derived from common assumptions, except for construction times and overnight costs that are specific to each reactor. The overnight cost of the first unit of the modular power plant includes an extra cost. Appendix 3 shows details of selected values.

	Multi-modular power plant		Large capacity power plant
	Module 1	Modules 2 to 4	
Construction time (months)	36	24	60
Discounted average cost θ_i (cents/kWh)	3.8	2.5	2.9

It will also be assumed that the predicted rate of increase of the price of electricity is $\alpha=0\%$, and that the standard deviation of price variations is $\sigma=20\%$, which is high. For a probability of 95%, the annual price variation will be within the range -40% to +40%.

5.1. Optimum investment strategy in high capacity

Remember that with this technology, the cost per kWh is estimated at 2.9 cents. Is it optimum to make this investment when the market price per kWh exceeds 2.9 cents? No, because the risk that this price will drop below the production cost is too great. Since the decision to invest is irreversible, it is important to wait for a specific value. The model presented in section 3 provides a means of determining which strategy maximizes the expected NPV of the profit flow from the investment. Due to high uncertainty on price changes, the optimum strategy of a neutral investor faced with the risk consists of waiting until the market price of electricity reaches the critical threshold $P^*=4.75$ *cents/kWh*, calculated here for n=1.

We can also calculate the expected net present value (ENPV) of the investment project for this high capacity power plant. We can use this later as a basis for comparison. This value depends on the current price of electricity. For example, the ENPV for the project can be estimated when the price is equal to 3 cents per kWh, equal to $F_1(3)=401.4$ €/kW. The following table contains a summary of the results for this project:

	Electricity production cost (cents/kWh)	Critical price threshold (cents/kWh)	ENPV (in €/kW) if P=3 cents/kWh
High capacity	*2.9*	*4.75*	*401.4*

Figure 2 shows the present value of the project as a function of the current price of electricity. For a present price P less than P^*, the project is not started, despite the fact that the project can have a positive value. The expected net present value increases non-linearly with the price P, as indicated by formula (2). At higher values, the investment option was used, and profits increase linearly with the price.

5.2. Optimum modular investment strategy

In the case of a modular investment, the production costs per kWh are equal to *3.8 cents* and *2.5 cents* for the first unit and for the three series units respectively. If we consider the first unit in isolation and forget the value of the option that it provides to construct three very cost-effective series units, the solution provided by the model in section 3 calibrated on this first unit results in a recommendation that the investment should only be made if the electricity market price exceeds *6.23 cents/kWh*.

	Electricity cost (cents/kWh)	Critical price threshold (cents/kWh)	ENPV (in €/kW) if P=3 cents/kWh
Isolated first unit	*3.8*	*6.23*	*263.2*

Section 4 explained how to include the value of the option due to modularity of the investment. This model leads to a recommendation to invest in the first unit as soon as the price of electricity reaches the critical threshold $P^*_n=4.29$ *cents/kWh*. The difference between the critical threshold obtained for a single unit and the threshold obtained with a first unit with the same characteristics is explained by the fact that the possibility of building more cost effective units following this first decision is taken into account.

Once this unit is operational, construction of unit 2 should be started if the price exceeds $P^*_{n-1}=3.57$ *cents/kWh* after the end of construction of the first unit. The following table contains critical prices associated with each module.

	Electricity cost (cents/kWh)	Critical price threshold (cents/kWh)
First unit	3.8	*4.29*
Unit 2	2.5	*3.57*
Unit 3	2.5	*3.79*
Unit 4	2.5	*4.10*

The value of residual options gradually reduces during construction of the modular system, consequently critical prices increase significantly, except for the first unit, allowing for the extra cost of this unit. Figure 3 shows a scenario for price changes and for implementation of this optimum strategy.

5.3. Comparison of the two projects

The following table summarizes optimum strategies for starting the two projects:

	Electricity cost (cents/kWh)	Critical price threshold (cents/kWh)	ENPV (in €/kW) if P=3 cents/kWh
High capacity	*2.9*	*4.75*	*401.4*
Modular project	*(3.8 ; 2.5)*	*4.29 (first unit)*	*442.2*

In this numerical illustration, the modular project will be built before the project for construction of a high capacity unit. The critical price threshold for the first unit is lower than the critical price threshold for the high capacity unit (*4.29 < 4.75*).

This tells us nothing about the comparison of net present values of cash flows generated by the two projects. But it can be seen that for a current price of electricity of 3 cents/kWh, the expected net present value of the modular project is higher than the expected net present value of the high capacity unit project (442.2>401.4). Therefore the flexibility of the modular project has two effects for the producer. Firstly, it incites him to make the investment sooner. Secondly, modularity increases the expected present value of the profit from the project. Figure 4 shows the ENPV per installed kW for the two projects when the optimum dynamic investment strategies are followed, as a function of the current price of electricity. In this simulation, it can be seen that the ENPV of the modular project is always greater than the ENPV of the high capacity unit project, regardless of the price of electricity. When the price of electricity is very high, the benefit of modularity is practically non-existent since the risk is low.

5.4. Alternative presentations of results

In the previous section, we saw that the modular project dominates the high capacity unit project in two ways: lower critical price and higher ENPV of future cash-flows. In this section, we will attempt to determine the necessary reduction in electricity production cost for the high capacity unit project, to bring the competitiveness of this technology to the "same level" as the modular project. There are two possible approaches, depending on whether we are interested in the critical price or the ENPV.

In the proposed simulation, the project to construct a high capacity power plant must be built after the modular project, since its critical price is higher. What reduction in the cost of electricity generated by a high capacity unit project is necessary for the two projects to be built at the same time, in other words for their critical prices to be identical? The following table contains the answer to this question.

	Electricity production cost (cents/kWh)	Critical price threshold (cents/kWh)	ENPV (in €/kW) if P=3 cents/kWh
High capacity	*2.9*	*4.75*	*401.4*
High capacity	*2.62*	***4.29***	*470.4*
High capacity	*2.73*	*4.48*	***442.2***
Modular project	*(3.8 ; 2.5)*	***4.29***	***442.2***

If the cost of electricity is lowered to 2.62 c/kWh, the critical price threshold is lowered to be the same as that for the first unit in the modular project. Nevertheless, if the price of electricity is this low, the high capacity project generates profits for which the expected net present value is significantly greater than the corresponding value for the modular project. The cost of electricity only has to be lowered to 2.73 c/kWh for the expected net present values to be identical for the two projects. Therefore, compared with the average cost of electricity for the modular project (2.825 c/kWh), the cost of electricity for the non-modular project that generates the same expected profit is only about a tenth of a Eurocent per kWh lower. This is a measurement of the value of the modularity.

Before making an investment, an investor wants prospects of a higher profit for a large unit investment than for a modular investment. Whereas production costs for the two solutions are equal in the reference case, we will show that investors might choose a technology with a higher production cost in return for greater flexibility.

5.5. Sensitivity analysis

5.5.1. Sensitivity of the optimum strategy considering the cost of electricity from the different units

In the reference simulation presented above, the costs of electricity of first units and series units are equal to 3.8 cents/kWh and 2.5 cents/kWh respectively. With this cost distribution, the critical threshold for the price of electricity triggering investment in the first unit is equal to 4.29 cents/kWh. We will examine the effect of a transformation of the costs structure on the critical price threshold. The following table gives an overview of this effect. Each cell in this table corresponds to a specific cost structure. The number in bold represents the critical price threshold (in cents/kWh). Below this number, we have shown the ENPV of profits (in €/kW) when the price of electricity is 3 cents/kWh.

\ SERIES UNIT FIRST UNIT\	2.0 cents/kWh	2.1 cents/kWh	2.2 cents/kWh	2.3 cents/kWh	2.4 cents/kWh	2 .5 cents/kWh
3.8 cents/kWh	**3.87** 531.1	**3.95** 510.84	**4.04** 491.95	**4.12** 474.29	**4.20** 457.76	**4.29** 442.25
4.1 cents/kWh	**4.03** 500.43	**4.12** 481.87	**4.21** 464.50	**4.30** 448.24	**4.38** 432.99	**4.46** 418.65
4.4 cents/kWh	**4.19** 472.78	**4.28** 455.72	**4.37** 439.72	**4.46** 424.71	**4.55** 410.60	**4.64** 397.31
4.7 cents/kWh	**4.35** 447.71	**4.45** 431.99	**4.54** 417.22	**4.63** 403.33	**4.72** 390.24	**4.81** 377.91
5.0 cents/kWh	**4.51** 424.86	**4.60** 410.34	**4.70** 396.67	**4.79** 383.79	**4.88** 371.64	**4.97** 360.15
5.3 cents/kWh	**4.66** 403.96	**4.76** 390.51	**4.85** 377.83	**4.95** 365.86	**5.04** 354.55	**5.13** 343.84

Any increase in costs, either for the first unit or for the series unit, will increase the critical price. Equation (4) showed that for a non-modular high capacity unit, the critical price is proportional to the cost of electricity. This is not the case mathematically when the investment is modular. Nevertheless, this table shows that the degree of non-linearity in the relation between the cost and critical price is small. As a first approximation, we can conclude that an increase in the cost per kWh of the first unit will only increase the critical price by half of this amount. Similarly, approximately 90% of the increase in the cost of electricity for series units is reflected in the critical price threshold that triggers the investment in the first unit.

This sensitivity analysis demonstrates cost configurations (in green in the table) for which it is optimum to build the first unit when the price of electricity reaches a threshold that does not cover the electricity production cost for this unit. In this case, the utility company decides to accept losses on the first unit, making the gamble that they will be compensated later on by electricity generated inexpensively by the series units. Thus, while for a large capacity non-modular unit, the entrepreneur will always wait until prices are greater than production costs before starting his investment, for modular units the investment might be triggered at prices insufficient to cover costs.

5.5.2. Transferring fixed costs to the first unit

In the reference example, the first unit produced electricity relatively expensively compared with series units due to the fact that a relatively large part of fixed costs for the modular assembly (infrastructure, common parts, etc.) is allocated to the first unit. Increasing this cost reduces the competitive advantage of the modular project. This can be verified in the table in section 5.5.1 in which transfers of this type are made. We can see that the average cost of electricity generated by the modular assembly remains constant in this table while moving along a secondary diagonal. Reducing the cost per kWh for each of the three series units by 0.1 cents increases the cost per kWh of the first unit by 0.3 cents.

An increase in the proportion of the fixed cost allocated to the first unit reduces the profitability and the flexible nature of the modular project, increases the critical price and therefore encourages the entrepreneur to delay his investment. However, since the increase in the critical price is slower than the increase in the production cost of the first unit, transferring fixed costs to the first unit leads to a situation in which the critical price is less than the production cost.

5.5.3. Increase in the discount rate

In our reference simulation, we considered a discount rate of 8% per year. In this section, we will examine the effect of increasing this rate to 10 and 12 percent. A change in the discount rate modifies the cost of electricity and also the optimum investment strategy. This increase is represented by an increase in the cost per kWh. It also penalizes waiting time and therefore encourages the entrepreneur to invest earlier. These two elements have contradictory effects on critical price thresholds, as can be seen in the table.

Discount rate	Electricity cost (cents/kWh)		Critical price threshold (cents/kWh)	
	High capacity unit	Modular project	High capacity unit	First unit
8%	*2.9*	*(3.8 ; 2.5)*	*4.75*	*4.29*
10%	*2.9*	*(3.8 ; 2.5)*	*4.52*	*4.13*
10%	*3.3*	*(4.5 ; 2.8)*	*5.14*	*4.77*
12%	*3.8*	*(5.2 ; 3.1)*	*5.70*	*5.28*

The first line in this table shows the data and results of the reference simulation. In the second line, the costs of electricity are left unchanged, but the discount rate is increased. The purpose of this simulation is to isolate the effect of the change in the discount rate on the optimum strategy. This demonstrates the effect of impatience that reduces critical prices. The third line takes account of the impact of the change in rate on the discounted cost of electricity. The consequence is to increase critical prices and this effect dominates the impatience effect. It should be noted that the modular project continues to dominate the high capacity unit project regardless of the discount rate. The increase in the discount rate acts on a high capacity unit project in the same way as on a modular project.

5.5.4. Reduction in uncertainty

Up to now, we have considered a very uncertain environment with an annual volatility of electricity prices equal to σ=20%. We will now consider the reference case assuming that the volatility of the price of electricity is only σ=10%. This means that there is an approximately 95% probability that the annual price variation will be within the range [-20%, +20%].

Volatility of market prices	Critical price threshold (cents/kWh)		ENPV (in $/kW) if P=3 cents/kWh	
	High capacity unit	First unit	High capacity unit	First unit
20%	*4.75*	*4.29*	*401.4*	*442.2*
10%	*3.72*	*3.63*	*217.8*	*218.1*

When the price uncertainty is low, the value of the waiting option is lower. Remember that waiting has a value for the additional information obtained by observing prices during this additional waiting time, before carrying out an irreversible investment action. Therefore, it will not be surprising that critical price thresholds are lower than in the reference case. Because the irreversible nature of the decision is much more significant for a high capacity unit than for the first module in a modular project, the drop in the critical price is much more significant for the first project. Thus, as price volatility drops, the advantage of the high capacity unit increases. Nevertheless, in the example given, it remains true that the modular project is started at a lower critical price (and therefore earlier) than the high capacity unit project. Finally, it can be seen that the expected cost effectiveness is practically identical for the two projects, with a volatility of 10%.

A drop in price volatility reduces the expected profitability of projects because it makes it less probable that they will be completed in the near future. As volatility reduces, the probability of reaching prices triggering the investment also reduces, and the effect is that it reduces the expected net present value of these projects. We could compare two situations to illustrate this point. In the first case, the price is certain and constant in time at a level *P* less than the cost of electricity. In this case, the project is never built and the profit is zero. In the second case, the current price is also P, but there is still some uncertainty about its future trend. Therefore there is a hope that one day the future price will reach the critical threshold and that profits will be generated.

6. Conclusion

The objective in this document was to illustrate a method for solving a problem of investment in a modular project. Since the future decision to continue the modular project or to abandon it (at least temporarily) will depend on market conditions at the time, it is no longer sufficient to use classical NPV rules to solve the investor' s immediate problem.

The use of the real options theory induces developments to the theoretical model that may be complex, but our numerical example tends to show that these calculations are possible. These developments show the importance of uncertainty and the calculation of option values. It also provides a means of determining approximate results of investment choices made by an electricity operator in a pure and perfect competitive universe:

- It is not optimum to invest in a high capacity unit as soon as prices reach complete production costs. The risk of a price drop reduces the attractiveness of an irreversible investment. Thus, an electricity producer is not encouraged to build a high capacity unit unless the price is higher than the full production cost, which could be considered as being "a risk premium" at which he will receive a sufficient profit amount with an acceptable probability.

- In the case of a modular investment, the "risk premium" expected by the investor is lower because he has better control over the market risk. In his decision to trigger such an investment, the electricity producer uses the sequence of opportunities offered with the first module, with the option to interrupt or extend the strategy at each decision making stage. In this case, it may even be optimum to invest in the first unit of a modular power plant before the market price reaches the full cost of electricity generated by this unit, which corresponds to a negative risk premium.

- A modular investment enables flexibility making it possible to adapt to uncertainty, and this is why it may be preferred to an irreversible high capacity investment, even if its production costs are higher. Thus in an uncertain environment, the choice with the lowest production costs is not necessarily the choice that maximizes the investor's expected profit.

- The lowest risk investment is not necessarily the lowest cost investment, and if all other factors are the same, a more flexible investment project will necessarily be preferred in an environment marked by price uncertainty.

Although the primary objective of this presentation was to propose a general methodology for determining the value of modularity in energy investments, we also wanted to give an overview of the consequences of modularity in specific applications of investment strategies for companies in competition. In particular, we considered an environment in which the cost of capital is 8% and the volatility of electricity prices is 20% (standard deviation of relative market price variations per year). We considered an investment project with a maximum capacity of four 300 MWe modules, in which 40% of the overnight cost is allocated to the first unit. We have shown that in this environment, the benefit of the modularity in terms of expected cost effectiveness is equal to a reduction of the order of one tenth of a Eurocent in the production cost per kWh. Therefore in conclusion, this benefit must be compared with the cost of modularity in terms of the loss of economy of scale possible with higher capacity units.

Note some limits of this work and possible extensions associated with it. One important assumption with our model is that the electricity producer's actions have no effect on changes to the price of electricity. This assumption is really not realistic in a market context limited by transmission constraints (costs, congestion). A competitive company risks losing its market if it waits too long before investing. For example, one company might build a high capacity installation as soon as the market price exceeds its costs, and ignore the value of the waiting option. The narrowness of the market could then be such that this increase in supply depresses prices in the long term, making other investment projects unprofitable for a long time. Therefore an extension to this work would consist of examining strategic preemptive behaviors.

In considering the behavior of different companies on the market, we also need to look at the impact of investment cycles. Ford (1999) demonstrated a price "boom" and "bust" phenomenon due to a similar analysis of price signals by different investors. The magnitude and frequency of the price cycle could significantly affect the relative attractiveness of different types of investment projects. The existence of these cycles on the electricity market could be included through a variation of the rate of increase of the price of electricity with time.

Finally, we assumed that construction options for successive modules have an infinite life. The industrial reality for construction of a multi-modular power plant makes it essential to include constraints that reduce the flexibility of such an investment. In particular, there must not be any excessive discontinuity in workloads in the construction schedule for the different modules, otherwise the investment cost could be significantly increased. The investor's margin for maneuver on the rate at which he makes his investments could be limited by fixing a maximum time between commissioning of two successive modules. Conversely, the construction sequence for the different modules could be shortened by allowing parallel construction, but this is not possible in the existing model.

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Appendix 1: Determination of the optimum strategy for the isolated high capacity unit.

As long as P has not reached the threshold P_n^*, the investment is not made within a time period Δt. By Bellman's Principle, it is deduced that

$$F_n(P) = e^{-r\Delta t} E\left[F_n(P+\Delta P)\right]$$

where ΔP is the random increase in price during the time interval $[0,\Delta t]$. If Δt tends toward zero, we obtain by Ito's Lemma that

$$e^{-r\Delta t} = 1 - r\Delta t$$
$$E\left[F_n(P+\Delta P)\right] = F_n(P) + PF_n^{'}(P)\alpha\Delta t + 0.5P^2 F_n^{''}(P)\sigma^2\Delta t$$

These three equations can be combined to show that

$$F_n(P) = (1 - r\Delta t)\left[F_n(P) + PF_n^{'}(P)\alpha\Delta t + 0.5P^2 F_n^{''}(P)\sigma^2\Delta t\right]$$

The final result after eliminating terms in $(\Delta t)^2$ that are second order infinitely small terms is

$$-rF_n(P) + \alpha PF_n^{'}(P) + 0.5P^2 F_n^{''}(P)\sigma^2 = 0$$

This differential equation must be satisfied within the price range within which it is optimum to wait. The solutions of this differential equation are in the form

$$F_n(P) = A_{n1}P^{\beta_1} + A_{n2}P^{\beta_2}$$

where β_1 and β_2 are the two roots of the following quadratic equation

$$-r + \alpha\beta + 0.5\beta(\beta-1)\sigma^2 = 0.$$

By associating conventional boundary conditions to this differential equation

$$F_n(0) = 0$$
$$F_n(P_n^*) = k_n P_n^* - I_n,$$

and adding the « smooth-pasting » condition to guarantee the optimum

$$F'_n(P_n^*) = k_n,$$

we obtain the expected NPV F_n for the project as a function of the price of electricity, and also the optimum critical threshold P_n*. The root $\beta_2 < 0$ is excluded since $F_n(0)=0$ must be true.

Appendix 2: Determination of the optimum strategy for unit *n-1*.

As long as *P* has not reached the threshold P_{n-1}^{*}, the investment is not made within a time period Δt. As in Appendix 1, it is deduced that:

$$F_{n-1}(P) = A_{n-1} P^{\beta} \quad when \quad P \le P_{n-1}^{*}.$$

When *P* reaches P_{n-1}^{*}, the decision is made to invest in unit *n-1*. It will generate a profit flow for which the expected net present value is equal to

$$F_{n-1}(P_{n-1}^{*}) = k_{n-1} P_{n-1}^{*} - I_{n-1} + e^{-rT_{n-1}} E\left[F_n(P_{t+T_{n-1}}) \middle| P_t = P_{n-1}^{*} \right].$$

The nature of the terms $k_{n-1} P_{n-1}^{*}$ and $-I_{n-1}$ is the same as in the previous case. The terms are the expected NPV values for income and costs respectively. The $e^{-rT_{n-1}} E\left[F_n(P_{t+T_{n-1}}) \middle| P_t = P_{n-1}^{*} \right]$ term corresponds to the option to invest in the last module. It updates the expected value of the option to build the last unit as soon as module *n-1* is finished, in other words T_{n-1} years after the decision to build module *n-1*. By combining the two equations in this inset with the smooth-pasting condition, we obtain:

$$F'_{n-1}(P_{n-1}^{*}) = k_{n-1} + e^{-rT_{n-1}} \frac{\partial}{\partial P_{n-1}^{*}} E\left[F_n(P_{t+T_{n-1}}) \middle| P_t = P_{n-1}^{*} \right],$$

and the result is a system of two equations with two unknowns P_{n-1}^{*} and A_{n-1}. This system cannot be solved analytically.

Appendix 3: Assumptions used in the illustration example.

The costs used in the illustrative example in sections 5.1 to 5.4 were obtained by setting the average total present value of the costs of the two power plants equal to each other. With this assumption, the modularity effect can be isolated. To achieve this, it is assumed that the operating mode and costs not related to the investment are identical for the two concepts. Therefore a difference in the average production cost (sections 5.4 and 5.5) can be allocated to the investment part alone.

In this illustration, it is assumed that the modules and the high capacity unit both operate with an average availability of 90% over a life of 40 years. Operating costs and fuel costs are taken to be equal to 60 € /kWe/year and 5 € /MWh respectively. The construction times mentioned in section 5 and a discount rate of 8% are used to determine bridging loan interest equal to 22% for the high capacity unit, 13% for the first module and 8% for the last module of the modular power plant respectively.

Moreover, an extra investment cost is allocated to the first unit, for which the assumed overnight cost is equal to 40% of the total overnight cost of the modular plant. These elements and a realistic value of an overnight cost for the high capacity unit can be used to express the average present value of the production cost for the modular power plant and to determine an average present value of the production cost per module. The consequence of this approach is to obtain an average total present value for the cost of the modular power plant slightly different from the algebraic average of the calculated costs for each module.

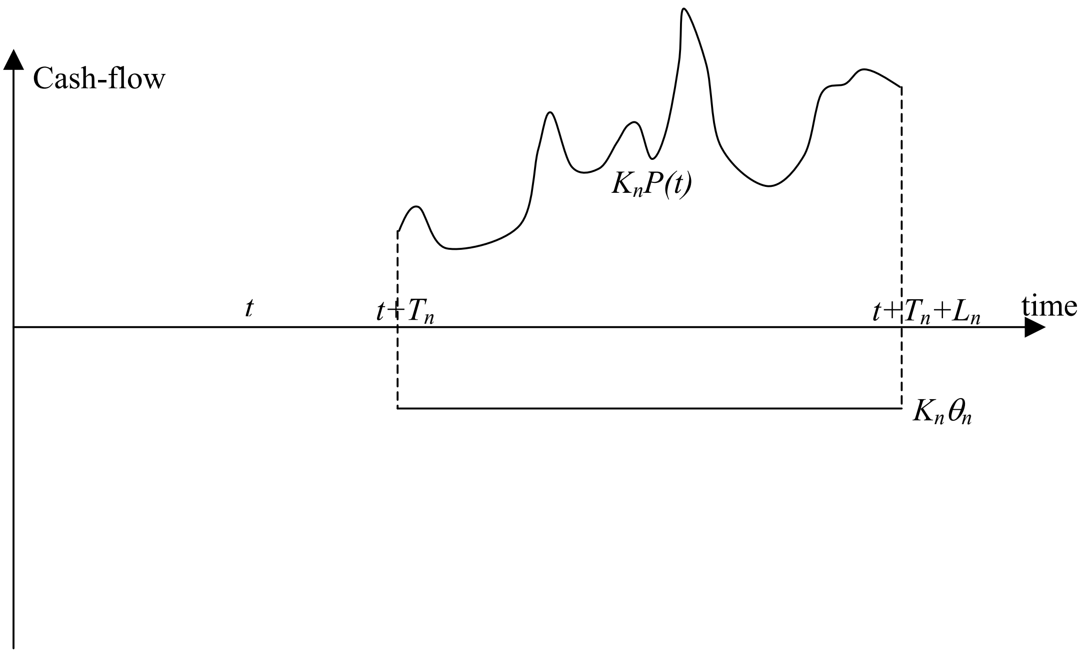

Figure 1: Chronology of cash flows for the last unit.

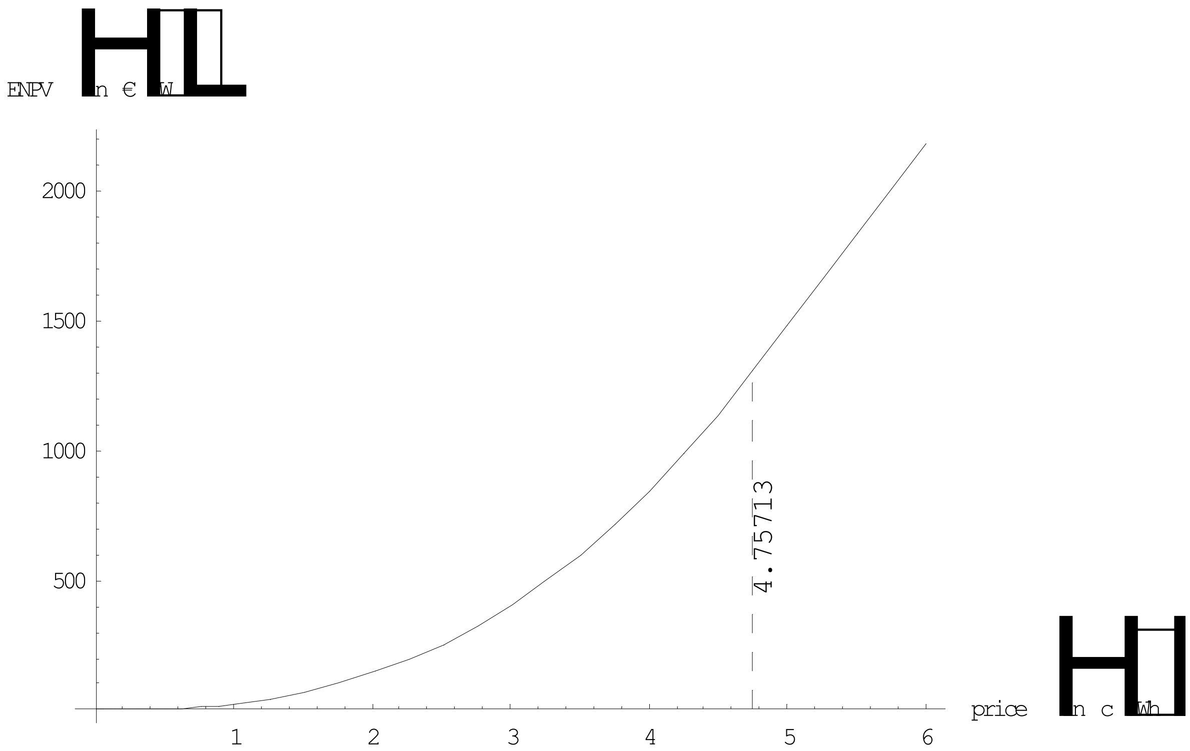

Figure 2: ENPV of expected profits as a function of the current price of electricity for a high capacity unit.

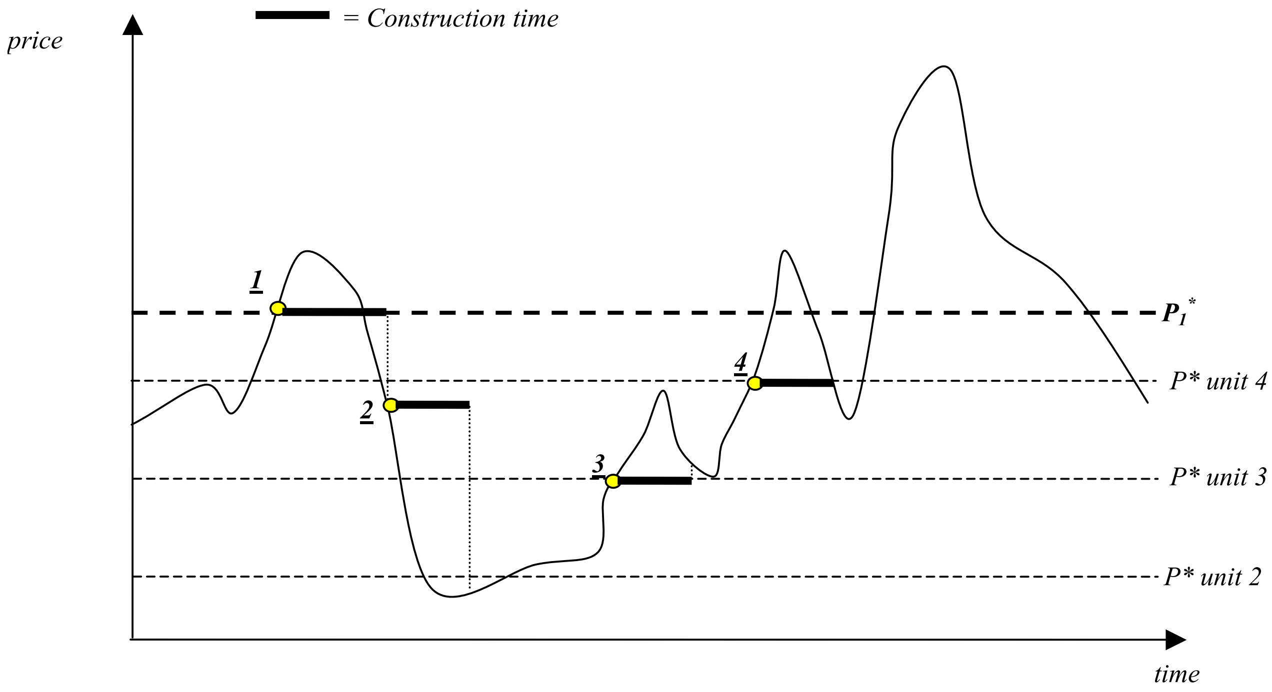

Figure 3: Example scenario for electricity price changes and application of the optimum investment strategy. At date **1**, the market price exceeds the critical threshold P^*_n=4.29 for the first time. The industrialist then decides to start construction of the first unit. Three years later, in other words at time **2**, the market price is still greater than the critical threshold P^*_{n-1} for unit 2, despite the drop in the market prices. Therefore the operator decides to continue building module 2 without interruption. But at the end of construction of module 2, the market price is too low, construction of the third unit is postponed and will actually start on date **3**, when the price is higher than the corresponding critical threshold.

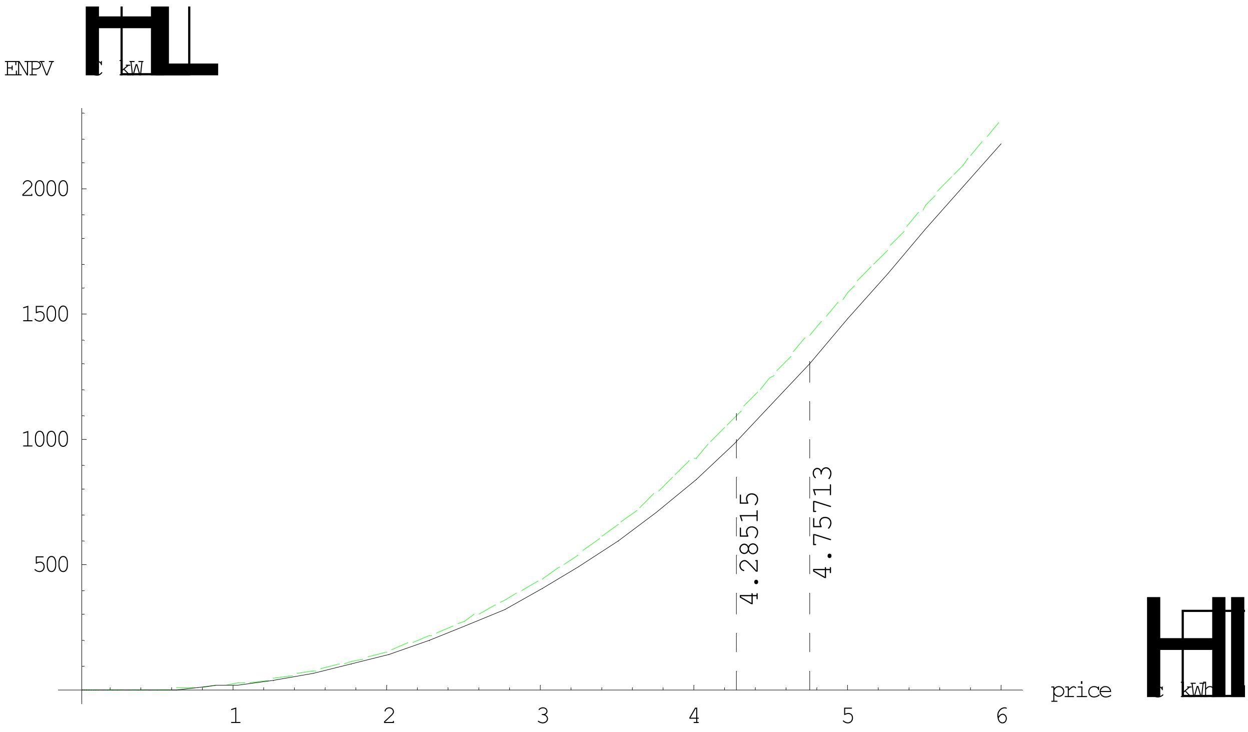

Figure 4: Comparison of two investment projects. The cross-hatched curve shows the optimum ENPV for the modular project, while the solid curve shows the optimum ENPV for the high capacity unit project.