THE FRENCH NUCLEAR PROGRAM: EDF'S EXPERIENCE

Bernard ROCHE
Senior Vice President
Nuclear Affairs
Electricité de France / Generation & Engineering

KEY WORDS:
French nuclear program – standardization – architect engineer.

Electricité de France developed in the middle of the seventies a large nuclear program (58 units), with a limited series of standardized PWRs. EDF, with a strong engineering division (around 4000 persons) was involved as architect engineer during the construction, but also the operations of the power plants.

The past experience and the economical efficiency of the new reactor EPR lead EDF to launch the construction of a first EPR on Flamanville site.

1. CONTEXT OF THE FRENCH NUCLEAR PROGRAM LAUNCH

1.1 Historical reminder

During the fifties and the early sixties, EDF began an ambitious hydroelectric program. During this period, EDF developed its experience as an industrial architect; the national company actively participated in the general project design, the establishment of contracts with subcontractors (civil works, electromechanical components, etc.) and the overseeing of construction operations.

In the second half of the sixties, the number of sites available for hydroelectric power production dwindled. Within the scope of its continued efforts toward diversification, EDF decided to turn to classical thermal (fuel oil) and to nuclear power generating plants involving a variety of different reactor types: pressurized water (Chooz A, connected to the grid in 1967, in cooperation with the Belgians), heavy water (Brennilis, connected to the grid in 1967, natural uranium gas-cooled (St. Laurent 1 and 2, Chinon 2 and 3, Bugey 1, commissioned between 1969 and 1972) and fast neutron (Phenix, connected to the grid in 1973). It should be pointed out that EDF's gas-cooled were essentially all different which lead to difficulties related to non-standardization (negative influence on costs, ease of operation, etc.).

1.2 The oil crisis of 1973 and its consequences

The gas-cooled plants quickly demonstrated their technological (graphite stacking fragility, low reactivity, sensitivity to the Xenon and Samarium effect) and economical (lack of standardization) limitations.

The French PWR program really took off in 1969 with the Tihange 1 Franco-Belgian unit. After that, construction of 1 or 2 PWR 900 MW pre-series units (named CP0) began each year from 1970 to 1975 at the Fessenheim and Bugey sites.

The 1973 oil crisis, with the oil embargo and the quadrupling of oil prices, clearly reminded France of its dependence (75% in 1973).

Nuclear power was the only possible means of reducing this dependency. In early 1974, the French government decided to undertake an extensive power generation program based on PWR reactors.

As a result, the French nuclear program comprises 58 PWR units (based on Westinghouse design for the first 54 units):

- 6	900 MW	pre-series reactors:	CP0 (Fessenheim 1 and 2 plus Bugey 1, 2,3,4)
- 28	900 MW	reactors:	CP1 and CP2
- 20	1300 MW	reactors:	1300 P4 and P'4
- 4	1450 MW	reactors:	N4 (Chooz B1 and B2, Civaux 1 and 2). These N4 reactors are totally French and are free from Westinghouse original licence.

Remark: one 1200 MWe fast neutron reactor (Superphenix at Creys Malville) was connected to the grid in the eighties, but was shut down in 1997 (due to political reasons).

2. ORGANIZATION FOR THE DEVELOPMENT OF THE FRENCH NUCLEAR PROGRAM

EDF decided to become deeply involved in the process by thoroughly implementing its ability as an industrial architect which it developed during the hydro and classical thermal power generation programs (with its various series: 125, 250, 600 and 700 MWe for the thermal plants).

Power plants are not ordered "on a turn-key basis". The plant is divided into sections including design, electromechanical and civil works engineering sub-assemblies. In this manner, EDF can open each of these sections up to the competition (except for the main primary system and its connecting circuits handled exclusively by Framatome and the turbo generator plant reserved for Alstom). This enables it to benefit from competitive pricing and to set up a long term partnership with the contractor retained for each section. In an extremely limited number of cases, the contract was split between two contractors; this has occurred particularity for the reactor building containment, for the installation of piping in the reactor building of 900 MWe units, depending on whether the unit had a even or odd number or for the cast elbows of the primary circuit. In exchange, this type of allotment system requires excellent control of the entire plant's operation – in short, the undeniable qualities of an architectural engineer. It should be pointed out that French nuclear safety regulations require the operator to defend its safety reports itself which has led EDF to invest in the plant process.

From these premises, we can conclude that EDF had to acquire the conceptual design of the plant, come up with the detailed design of the systems with the help of subcontractors, monitor the construction operations and defend the reports before the Safety Authorities.

The economical interest of the allotment concept was reinforced by the standardization policy which was the cornerstone of the French nuclear power program (see § 3). We can estimate that our allotment standardized system was able to decrease the investment cost by 30-40%.

During the operations of the power plants, the engineering division become in charge of the modifications of the plants, and of the maintenance of the safety reference state. In case of technical problems, the engineering division also supports the plants by finding solutions to technical problems. The engineering division is also an intermediary between R&D and the operations.

3. THE CONCEPT OF STANDARDIZATION FROM DESIGN AND INSTALLATION TO OPERATIONS

EDF's choice consisted in trying to maintain the concept of standardization throughout the plant' service life.

3.1 Standardization of engineering and design

A review of the various possible sites showed that it was possible to work out standard design basis rules which would be accepted by the French Safety Authorities at all locations.

A nuclear program developed at several sites over a period of a few decades comes up against two main types of limitations:

a Each site is characterized by specific conditions relating to geology, seismicity, human geography, industrial environment, by a determined heat sink (flow, chemical quality, etc.) and by a neighboring power grid with its specific characteristics. It would have been anti-economical to group all site conditions together to define a design standard; the choice made consists in defining a standard which could be adapted to each of the sites with a minimum of modifications. In practice, this was possible and only the foundations, the cooling water systems and the connections to the power transmission network differ from one site to another: nearly all conventional or nuclear island systems are strictly identical as concerns the various units of the same series. The components are identical, their general manufacturing specifications and their installations are the same except for possible differences in symmetry.

b The second absolute limitation of a design standard concerns technological developments. Should the design be stabilized over a long period of time in order to be able to fully benefit from standardization or otherwise allow for technical improvements or appropriate modifications of safety and design basis rules? The compromise that was agreed upon consisted of having different plant series: 4 standardized plant series for the 900 MWe reactors (Fessenheim, Bugey, CP1 or contract program No. 1, CP2 or contract program No.2), 2 series for the 1300 MWe reactors (P4 and P^I4) and a single plant series, for the N4 1,450 MWe reactor.

   For example, in comparison with Fessenheim, the Bugey units have a higher thermal output (from 2660 MW to 2785 MWe) and an enhanced containment design pressure (4,7 to 5 bar). Shifting from the "Bugey" design to the "CP1" design, we notice an increase in the height of the reactor building and an equipment hatch which rises from ground level to mid-height of the reactor building containment. Continuing on from CP1 to CP2, the turbine building which was used for a pair of units and parallel to the axis formed by the centers of 2 paired reactor buildings is split, each turbine building being perpendicular to the axis formed by the centers of both reactor buildings (the major interest of this modification is to avoid the risk of missiles coming from the turbo generator vis-à-vis the reactor).

Simply speaking, the equipments inside the plants of the same series are identical and they are laid out in the same manner. The only differences concern the foundations (for example, at Cruas, considering the site's seismicity, the foundation raft had to be installed on aseismic bearing pads), the heat sink (certain units are cooled directly by the river, others use seawater or cooling towers) and the connection to the power grid.

Additional concepts must be discussed if a more in-depth analysis is to be considered: within the same series, feedback may lead a builder to modify a chemical composition or a manufacturing process. Furthermore, when two manufactures supply the same item, even though the general manufacturing specifications provided by EDF are the same, the manufacturing process can be slightly different which leads to varying inservice behavior.

Another example of destandardization can be seen with the aggregates used in the fabrication of concrete. For obvious reasons, the aggregates are taken from land surrounding the site. Their characteristics thus varies from site to site which explains why certain containment buildings experience creeping problems while others of the same series do not.

As a summary, we can say that at a general level all plants belonging to the series look the same even if at a detailed level some minor differences exist. This partial destandardization protects us partially against generic defaults that could affect all our units at the same time while giving to us the following advantages of standardization:

- Engineering manpower for design, quality control and assurance totals about 5 million man-hours for a first-of-a-kind unit and less than 1 million man-hours (basically attributed to site adaptation studies) for the following identical units.

- Lessons learned at all stages of field work save both time and money; for instance, field manpower was about 29 million man-hours for the first two pairs of units at the Gravelines power station, and only 13 million for the third pair. Although more difficult to assess, fabrication costs most certainly benefit from standardization also.

- The allotment system, in conjunction with standardization, incites competition among suppliers resulting in the best prices for components, and construction tasks. Subcontractors are able to plan their work schedule on a long term basis, which helps reduce costs.

Standardization is also advantageous in terms of the execution time table. Consider the 900 MWe series, for example: for the earlier Fessenheim and Bugey units, the delivery time from vessel commitment to first connection to the grid was between 75 and 80 months, but then dropped to between 55 and 65 months for the last 10 plants (of the "900 MWe" series) connected to the grid.

3.2. Standardization and backfitting policy

The policy of successive series which ensues from technological progress and the need to improve safety and the operability of units does not exclude that the units already built are backfitted, on the contrary. It is under this condition that the French Safety Authorities accepted the "per series" standardization principle. These backfitting operations must not challenge the general plant design and must not be carried out at frequent intervals: the Safety

Authority has informed EDF that plant backfitting operations must be carried out a ten-year basis (this period providing a certain stability within the safety reference frame). In practice, a batch of backfitting operations on a series is carried out over several years. Thus, the second ten-year safety reassessment of 900 MWe reactors started in year 1998 and will be achieved in 2010; for 1300 MWe reactors, this special outage began in 2005 for the first unit and will end in 2013 for the last unit. As a consequence, at any given moment, all the units within the same series are not all identical which represents also a limit to standardization.

In addition to backfitting operations which are derived from operational feedback and which leads to an improvement of safety-operability combination, mention should be made of the backfitting associated with generic defects within the park in operation (a negative consequence of standardization). The best examples concern the corrosion of steam generator tubes or the cracks on the vessel heads detected at control rod mechanism penetrations. In the case of the vessel heads, EDF decided to replace all covers of 900 and 1300 MWe reactors. In the case of the steam generator tubes (for which the replacement cost is higher, at approximately 100 M€ per unit), all of the 900 and 1300 MWe reactors are potentially concerned due to the sensitivity of Inconel 600; in fact, all of the steam generators (SG) will not have to be replaced: some Inconel 600 SG have had a thermal treatment that reduced the risks of problems; some SG are made of Inconel 690 that resists to corrosion .

In practice, EDF recorded relatively few generalized generic defects at all units. This success is explained by the initial choice of a proven design (the 900 MWe plants had an American “reference plant”) and the series policy (benefiting from the feedback, although possibly negative, from earlier series).

3.3. Operation standardization

For various reasons the organisation and methods on the different sites are not identical but the general operating rules, the technical specifications and the operating instructions are, in theory, identical for all the units in a series. This ensures proper homogeneity of operations within the same series; the advantages of such a policy are obvious:

- easy integration of operational feedback between identical units,
- personnel can move from one unit to another of the same series without any special training, thereby enhancing labour mobility (and better flexibility),
- a reduction in the required number of control simulators,
- control error risks are reduced, thereby enhancing safety,
- the work necessary for the drawing up instructions and procedures is lightened,
- reduction in the number of replacement parts in storage.

3.4. Conclusions about standardization

In building its nuclear program, EDF has implemented an extensive standardization policy encompassing design, components, backfitting and operation throughout the service life of the plant. As a result, the units within the same series have identical components, identical layout, identical operating instructions and an identical safety analysis report (with adaptations for the specific site). The advantages of such a program are obvious: lower engineering costs, lower component and installation costs and lower spare parts and operator training costs.

The drawbacks of standardization are essentially limited to the generic defects, although they are not extensive as one may be lead to imagine: there are different series, on the one hand, and on the other hand, if we examine the situation closely, in reality two units of the same series do not necessarily have the same operating history, nor the same conditions (thermomechanic loads, integration of modifications, etc.). When the details are examined, this "destandardization" increases when we shift from design to installation then to operation and it is this "de facto destandardization" which prevents unfavourable situations from spreading throughout the entire fleet. **In practice and as experience has shown, the financial advantage provided by standardization is largely greater, by at least a decade, to the inconveniences associated with the generic defects.**

4. PERSPECTIVE FOR NUCLEAR IN THE FUTURE IN EUROPE AND FRANCE

Investment in power generation facilities play a crucial role in the economic and electrical performance of the electricity sector, a fact that is amply illustrated by two figures, without even mentioning the weight of potential failure or concerns of electrical autonomy. Power generation accounts for up to two thirds of the costs borne by an integrated electricity utility (generation, grids, marketing); it generates 40% of CO_2 emissions in OECD countries (compared with 25% for transportation).

4.1. The market situation in Europe

Evidence of the relative inefficiency observed with regard to power generation facilities and their regulation methods has led electricity markets to open up to competition, starting in the late seventies in the United States. Provided that the grid is flexible enough, market prices will reflect the most efficient generation costs and will provide incentive for investing judiciously and opposing uncompetitive monopolies. Global competition revolving around technology design and power plant construction will necessarily be extended to the owners and operators of power generation facilities.

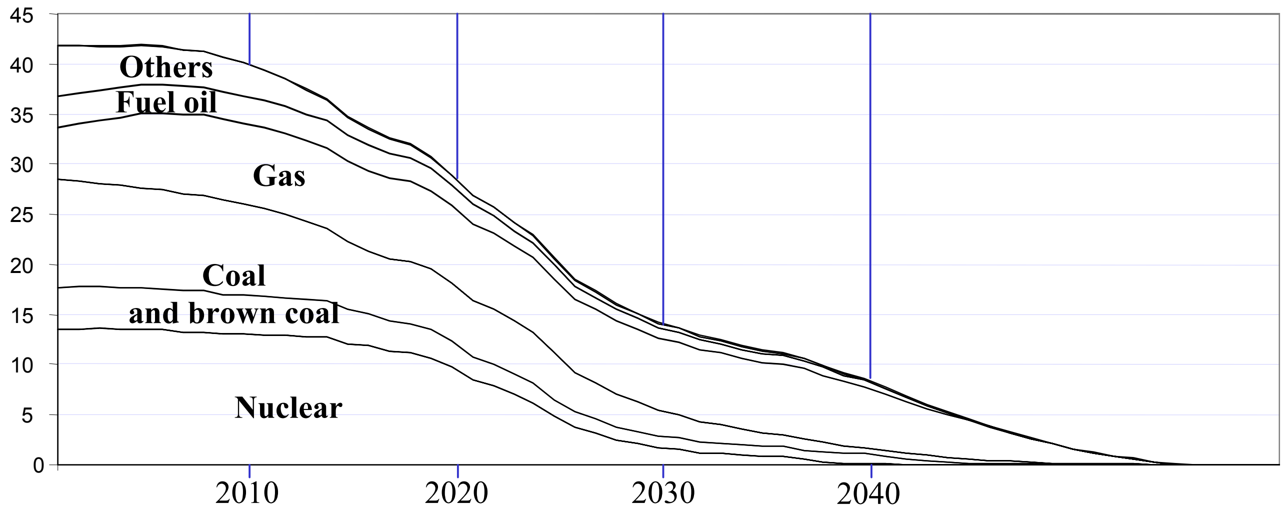
During the nineties, power generation capacity was sufficient, not to say excessive. Preoccupations turned towards short-term efficiency, difficulties encountered with setting up a market structure in the place of technical and economic management of generation plants, volatile prices and the matter of mercantile power that even a minor player could enjoy.

With the California crisis in 2000-2001, the downfall in 2002 of independent electricity producers emulating a "merchant plant" model, failures appearing on both sides of the Atlantic in 2003, and the soar in the price of fossil fuel, the challenge for fostering competition for the sake of sustainable performance became a priority once again. This entails selecting the most efficient investments and above all, activating them once they become necessary. Player strategy is visible proof of this change: following a brief period of attraction towards the mercantile or purely business model, ownership of tangible assets is being sought.

This very real situation within the industry is highlighted by Europe's need for new facilities by the year 2020. The present fleet which mainly comprises fossil-fuel plants is aging and is exposed to environmental constraints. More than 100 GW of thermal and nuclear energy will have to be replaced (including one-half of installed coal-lignite plants), as is shown in figure n° 1.

Figure 1

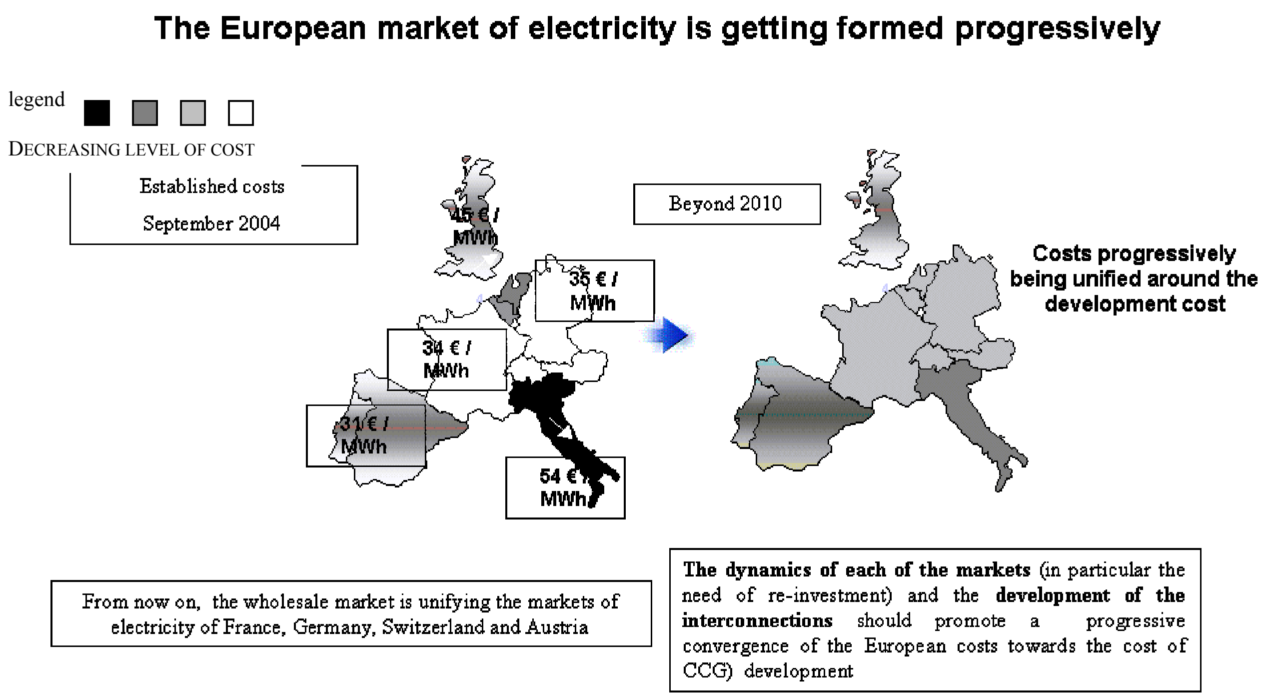
THE EUROPEAN THERMAL AND NUCLEAR FLEET RETIREMENTS Installed capacities GW



Because of the rise in demand, albeit modest and curbed by efforts to gain control over the latter, and in spite of renewable energies being developed in response to rising demand, this increase is expected to necessitate the installation of an additional 100 or so GW within the next twenty years. In total, foreseeable investment in power generation, heavy maintenance and modernisation could amount to around 200 billion Euros. The total amount of owner's equity and debt incurred be the seven leading electricity utilities in continental Europe (balance sheets for year 2003) barely exceeds this sum.

As you see hereafter on figure 2, the European market of electricity is getting formed progressively (the capacity of transmission lines limiting the exchanges for the time being).

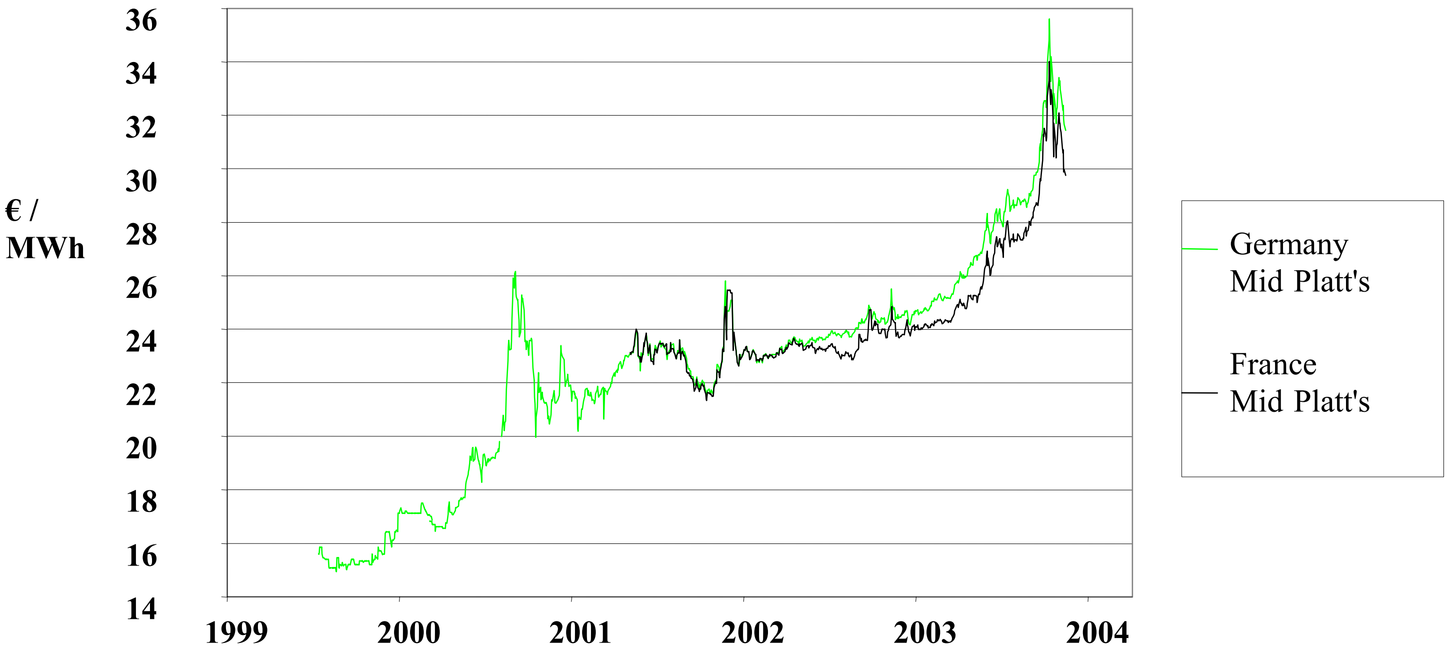
Figure 2



As the market becomes more and more efficient the signal given by the level of prices is more and more accurate. The figure 3 hereafter shows a dramatic increase of prices in France and Germany.

Figure 3

YEARLY AHEAD PRICES IN FRANCE AND IN GERMANY



In year 2005, the prices (for base load) are still increasing (45 €/MWh in August 2005 and 56 €/MWh in December 2005). This level is close to the development cost of a new combined cycle or a new nuclear reactor (like EPR).

Indeed, prices signalling the need to invest have already been reached in countries barely connected to the continental sector: Italy, United Kingdom and the Netherlands.

A same analysis of needs for peak or semi-base load facilities draws similar conclusions, including the possible installation of new facilities (combustion turbines or gas combined cycles) in France by 2010-2012. In March 2006, EDF decided the construction of 500 MWe of gas turbine for peak load.

4.3. New nuclear versus natural gas or coal

Development costs can be used as a basis for comparing various generation technologies requiring capital investments of different magnitudes. This method is used by the Ministry of Industry for establishing “reference costs”. The discount rate, when translated into more financial terms, represents the average weighted cost of capital among the majority of major electricity utilities in continental Europe.

In figure n° 4, two gas price hypotheses illustrate how sensitive the gas-combined cycle is to this key parameter (two thirds of total cost). The cost of CO_2 (15€/ton of CO_2) emissions, introduced in a spirit of relative consensus over the long term, penalises coal but does not in principle signify the exclusion of this source from a future energy mix. A conservative discount rate of 8% has been taken into account.

Figure 4

€03/MWh COSTS	PULVERIZED COAL	CCG (3,6€/Mbtu)	CCG (4€/Mbtu)	EPR FOAK	EPR AVERAGE UNIT -SERIES OF 10- (1)
Investment	13,3	6,1	6,1	24,8	17,8
Operation	7,0	3,7	3,7	5,9	5,9
Fuel	13,9	27,7	28,9	5,1	5,1
Taxes	2,3	3,3	3,3	2,4	2,4
TOTAL	**36,5**	**40,8**	**42,1**	**38,2**	**31,2**
CO_2 (2)	12,2	5,8	5,8	/	/
TOTAL WITH CO_2	**48,7**	**46,6**	**47,9**	**38,2**	**31,2**
(1) Average cost of a series of 10 units (including the foak) (2) CO2 on the basis of 15 €/t **NOTA :** actual cost of gas in Europe > 4.5 €/MBtu (UK NBP Gas)					

The first EPR is intrinsically competitive compared with the gas-combined cycle, with costs of similar magnitude i.e. 40 €/MWh. This balance ceases to exist as soon as significant CO_2 penalties are imposed, unless one reckons on much lower gas prices of around 3 €/Mbtu. Taken as a whole however, an EPR series offers a wide margin in terms of competitive edge.

For companies able to entertain the nuclear option and likewise for electricity consumers, this margin will be all the more easily turned to profit with industrial processes under control and a truly European market taking root with the commencing investment cycle.

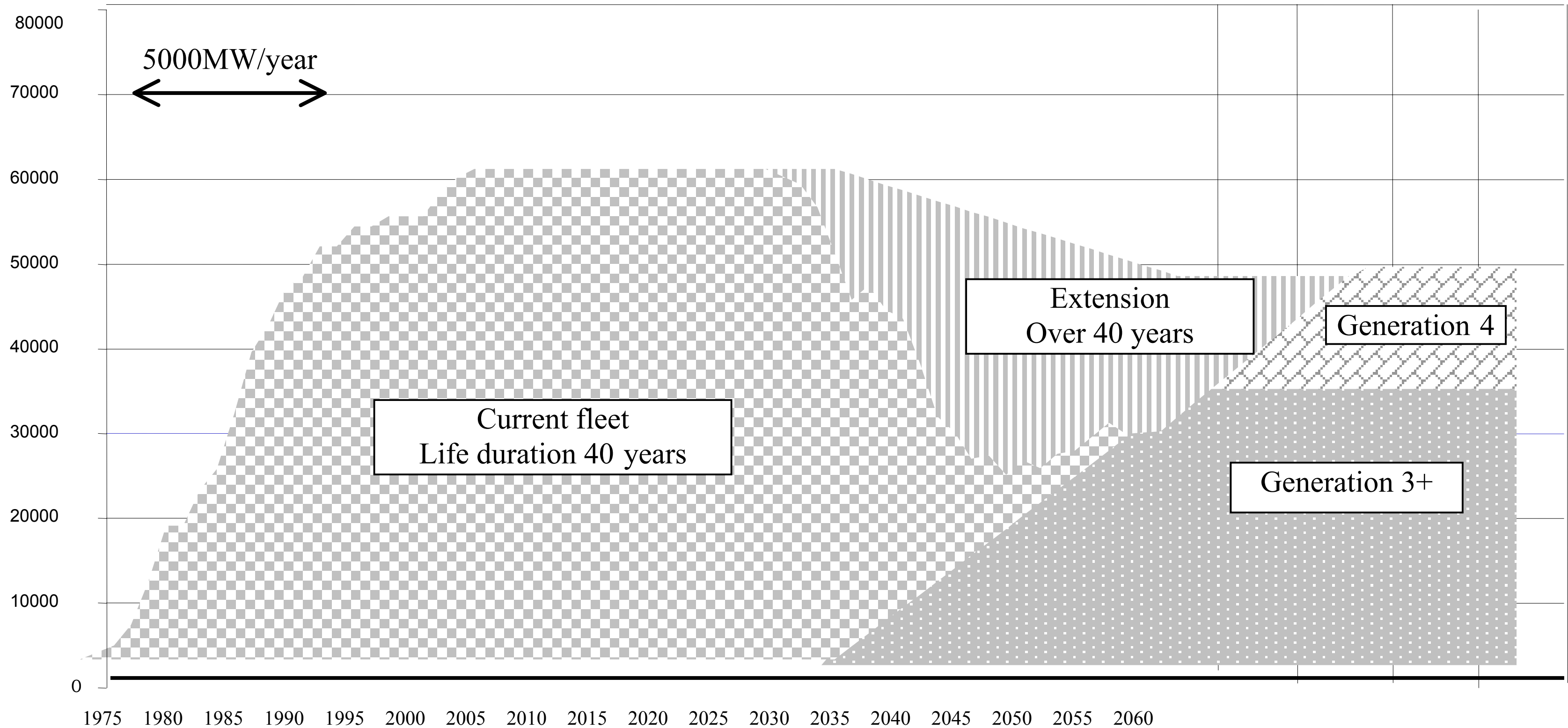
4.4. EDF decision to launch the first EPR

It is difficult to know precisely the time at which the electricity prices will be durably high, but we can guess that in the next decade, the prices will exceed permanently the development cost of a new nuclear power plant (NPP).

In fact, the precise date for launching a new series of NPP will depend on the proportion of nuclear in our future energy mix, on the life time of our existing units, on the number of MW that we will able to commission each year, on the growth of electricity consumption. You can see on figure n° 5 hereafter a scenario that implies the life extension of our existing units to 50 years (average value) and the connection to the grid of the first new units of the series around 2020.

Figure 5

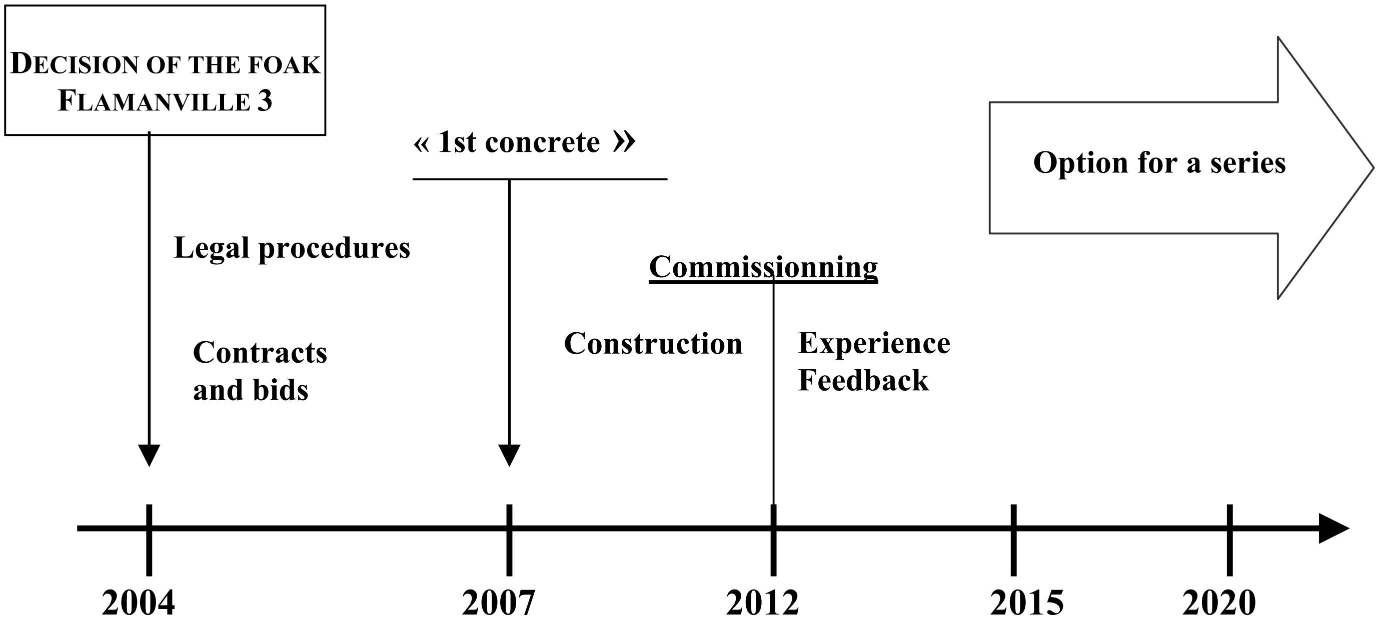
RENEWAL WITH 50 GWE WITH GENERATION 3 AND 4 OVER 30 YEARS (2020-2050)



Life duration average of the fleet : ≅ 50 years

In order to be ready to launch the construction of a series in 2015 with enough feedback of experience of operation of the EPR Foak, it was necessary to launch the first EPR in 2004. See below the milestones of the first Flamanville 3 EPR (Figure 6).

Figure 6



In line with the energy bill adopted after its first reading by the French National Assembly in June 2004, EDF has just started preparing the ground on the Flamanville site for the construction of an EPR plant, the first-off of a plant series that could be expanded further. Commissioning is scheduled for 2012.

5. CONCLUSIONS

The experience of EDF about nuclear is very positive: with standardization of construction and powerful internal skills about architect engineering, EDF was able to take advantage of a very competitive tool. In the future EDF will stick to the same kind of nuclear policy and EPR is our choice.