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# The costs of the French nuclear scale-up: A case of negative learning by doing

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ABSTRACT

The paper reviews the history and the economics of the French PWR program, which is arguably the most successful nuclear-scale up experience in an industrialized country. Key to this success was a unique institutional framework that allowed for centralized decision making, a high degree of standardization, and regulatory stability, epitomized by comparatively short reactor construction times.

Drawing on largely unknown public records, the paper reveals for the first time both absolute as well as yearly and specific reactor costs and their evolution over time. Its most significant finding is that even this most successful nuclear scale-up was characterized by a substantial escalation of real-term construction costs. Conversely, operating costs have remained remarkably flat, despite lowered load factors resulting from the need for load modulation in a system where base-load nuclear power plants supply three quarters of electricity.

The French nuclear case illustrates the perils of the assumption of robust learning effects resulting in lowered costs over time in the scale-up of large-scale, complex new energy supply technologies. The uncertainties in anticipated learning effects of new technologies might be much larger that often assumed, including also cases of "negative learning" in which specific costs *increase* rather than decrease with accumulated experience.



## 1. Introduction

The French nuclear Pressurized Water Reactor (PWR) program is legitimately considered as the most successful scaling-up of a complex and capital-intensive energy technology system in the recent history of industrialized countries. Starting in the early 1970s, France built 58 PWRs with a total gross installed capacity of 66 GWe. On completion in the year 2000, they produced some 400 TWh/yr of electricity, or close to 80% of France's electricity production (76% in 2008, EIA, 2009).

Successful scaling-up of a new technology entails three dimensions: An increase in technology deployment that is (a) *substantial* (80% nuclear in the electricity mix), (b) *rapid* (50 GWe, or 75% of the total installed gross capacity went "on-grid" within the decade 1980–1990), and (c) *systemic* (developing the industrial capacity to manufacture PWR components, the capability of building reactors within—by international standards—astonishingly short construction times, and developing a domestic industry covering the entire nuclear fuel cycle from enrichment, fuel manufacture, and reprocessing to nuclear waste management).

On all three counts, the French nuclear PWR program stands out as the most successful of comparable efforts worldwide. While the reasons for this success are specific to the French political/technocratic system, and may not be replicable in other countries (not even in France in the new Millennium), the economic dimensions, especially the costs, of this nuclear scaling-up have remained shrouded in mystery for a long time.

The prime objective of this paper is therefore to "get the data out" (Section 4). The paper synthesizes an "economic history" of the French nuclear program by drawing for the first time on raw data that, whilst publicly available since 2000 (after the program was all "*faits accomplis*"), have nonetheless to date largely escaped wider scientific scrutiny both in France and abroad. As will be argued below, the key to the French nuclear "success" story (at least in terms of implementation, the economic side of the program is more ambiguous as even the French experienced substantial cost escalation as shown below) was in a unique institutional setting, which requires to also provide the reader with a brief description the scale-up (Section 2) and its associated institutional landscape (Section 3). (It is beyond the scope of this paper to write a comprehensive social/political history of the French nuclear program.) Finally, some general lessons from this particular case study mainly in terms of the inherent pitfalls of cost forecasting (for instance embracing the perspective of

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"learning/experience curves") of complex, novel technologies will be drawn (Sections 5 and 6).

## 2. Scaling-up nuclear

It is no coincidence that scholars (e.g. Thomas, 1988) of the history of the French nuclear industry have classified its various development periods after the reigning presidents of the French Republic, indicating the strong linkages between government policies (including direct involvement) and the development of the industry. The rhythm of the program and the main technology characteristics of reactor designs are summarized in Table 1 and Fig. 1. The final resulting technology "map", which remains currently valid, is illustrated in Fig. 2.

A more detailed discussion of the institutional political-economy history of the program is beyond the space limitations of this paper. Interested readers are referred to Grubler (2009) for a more detailed summary discussion and to the insightful and detailed accounts of Bubb and Derian (1978), Thomas (1988), and Finon and Staropoli (2001) and the factually rich (but somewhat self-congratulating) study of Bataille and Galley (1999), complemented by the critical texts of Schneider (2008) and Marignac et al. (2008) and the controversy between Kidd (2009) and Schneider (2009b).

## 3. Anatomy of a success

Much has been written on the reasons for the success of the French nuclear scale-up. Among the various interpretations (technologic, political/institutional, economic), the institutional one (e.g., Finon and Staropoli, 2001) offers the most salient and integrative "storyline" of France's nuclear success, at least in the view of this author.

Following Jasper's (1992) perceptive analogy from Greek mythology the main groups of actors in a nuclear scale-up are "*gods*" (governments), "*titans*" (large industries and utilities—see Box 1 Institutional Actors), and finally "*mortals*" (the general public). The institutional key to success in France was the extremely limited number of institutional actors: "mortals" never played any decisive role either in the technocratic decision-making process or in hindering rapid expansion. The senior actors were extraordinarily well coordinated through the "invisible hand" of a small technocratic elite—the state engineers of the *Corps d'État*, especially the *Corps des Mines* (prevalent in the government and the CEA) and *the Corps des Ponts* (prevalent in ÉDF's equipment department). In other words, "god" (the French government) and the two titans that really mattered, the nationalized utility ÉDF and the state nuclear R&D organization CEA acted in a well-coordinated way, overcoming inevitable rivalries and differences of opinion. They ended up with a clearly formulated vision, mobilized the necessary resources, and proved quite apt in executing this extremely large-scale and complex

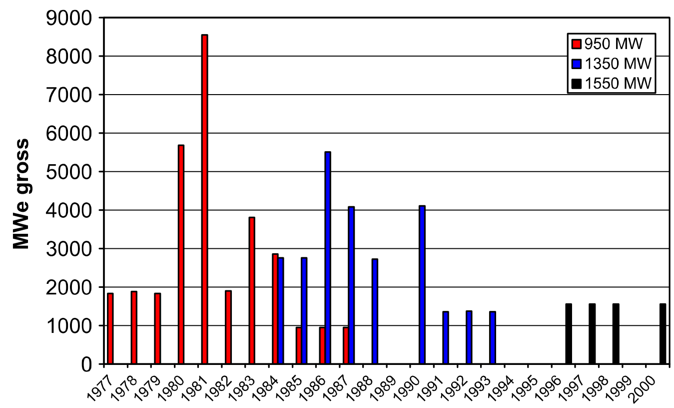


**Fig. 1.** Rhythm of the French nuclear PWR program (grid connections of MWgross by major size type). *Source*: IAEA PRIS data base (2009).

**Table 1**
Overview of the French PWR program.

| Order series | Reactor type | Reactor size typical MWnet (mean MWgross) | Number built | Constructed between | Mean construction time months | Mean investment costs "best guess" and (uncertainty range) 1000FF98/kWgross | Sites |
|---|---|---|---|---|---|---|---|
| CP0 | PWR<br>Westinghouse license | 900<br>(927) | 6 | 1971–1979 | 63 | 4.9<br>(402–5.9) | Bugey<br>Fessenheim |
| CP1 | As CP0 | 900<br>(949) | 18 | 1974–1985 | 65 | 5.5<br>(5.0–6.0) | Blayais<br>Dampierre<br>Gravelines<br>Tricastin |
| CP2 | As CP1 | 900<br>(955) | 10 | 1976–1987 | 67 | 6.5<br>(6.1–7.2) | Chinon<br>Cruas<br>St. Laurent |
| P4 | 1.3 GW PWR<br>Westinghouse license | 1300<br>(1382) | 8 | 1977–1986 | 78 | 6.9<br>(6.5–7.1) | Flamaville<br>Paluel<br>St. Alban |
| P'4 | P4 "frenchified"<br>Westinghouse | 1300<br><br>(1366) | 12 | 1979–1993 | 90 | 8.4<br><br>(8.0–8.8) | Belleville<br><br>Cattenom<br>Golfech<br>Nogent<br>Penly |
| N4 | PWR<br>New French design | 1500<br>(1561) | 4 | 1984–1999 | 126 | 11.0[a]–13.3<br>(10.3–14.5) | Chooz<br>Civeaux |
| EPR | EPR<br>Framatome-Siemens | 1600<br>(1650) | 1 | 2007– | Under construction | n.a | Flamanville |

[a] Lower range excludes Civeaux-2 reactor.

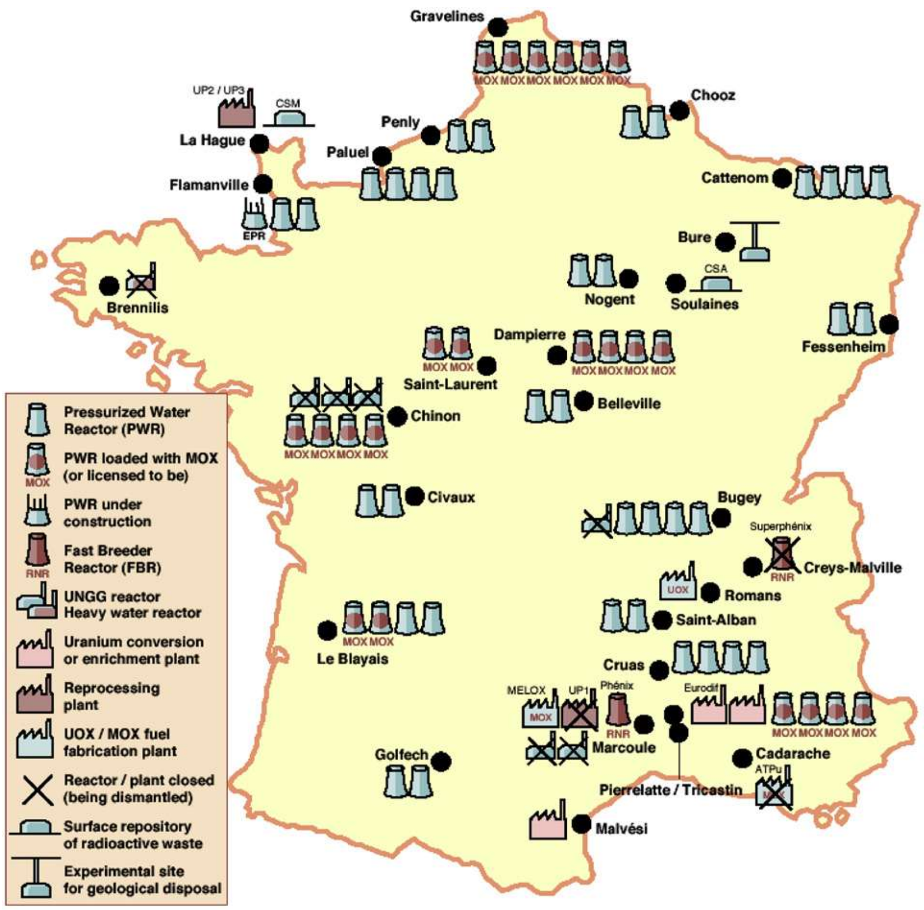


**Fig. 2.** Map of French nuclear installations. *Source*: Marignac et al. (2008: 36).

**Box 1–**The French Institutional Actors

The main French actors include the nationalized utility *Électricité de France* (ÉDF) and the state R&D agency *Commissariat pour l'Énergie Atomique* (CEA) whose rivalry over reactor design (the CEA favoring French designs and ÉDF favoring larger-scale, US licensed pressurized water reactors [PWR]) while being legendary were nonetheless resolved in 1970, paving the way to the nuclear scale-up. *Framatome* emerged as the main manufacturer for nuclear components, *Alsthom*, for turbines and generators; and in 1976, COGEMA for the entire fuel cycle, including the *Eurodif* enrichment facility and the *La Hague* reprocessing facility. The CEA, whose influence and prestige had somehow suffered in its losing the ''reactor battle'', quickly reaffirmed itself as 100% parent of COGEMA and a shareholder in Framatome. In 2001, Framatome and COGEMA (now AREVA NC) merged to form AREVA, essentially owned by the CEA, i.e., the French government. Also, AREVA entered a joint venture with Siemens of Germany in the development of the European Pressurized Water Reactor (EPR), and Framatome ANP was founded with a minority Siemens stake, renamed AREVA NP in 2006. In 2009, Siemens announced its intention to end its partnership, selling its 34% share back to AREVA. Under the contractual terms AREVA is obliged to buy back the Siemens shares latest by 2012.

We exclude the French regulatory bodies as either residing within government (the Ministry of Industry) or being controlled by the CEA in this taxonomy, as there is no documented incidence in 1970–1999 in which they acted truly independent of, let alone *against*, the nexus of the dominant government institutions—our ''Gods'' and ''Titans''. (In a significant change from past practices, the French regulatory authority ASN ordered a construction stop at the EPR Flamanville site in 2008 for a few weeks in order to ensure improved documentation and implementation of quality standards for concrete, welding, and steel framing. http://www.greenpeace.org.uk/blog/climate/construction-stopped-on-french-flagship-nuclear-reactor-20080527 (The original letters referred to in the article have been removed from the ASN website).

technology program, not at least thanks to the formidable engineering resources, personnel, and know-how of ÉDF. (As the recent experience at Flamanville, the site of France's first EPR reactor construction, has shown [substantial construction delays, quality assurance problems in pouring concrete, etc.] ÉDF's once formidable institutional know-how seems to have atrophied providing a good example of *knowledge obsolescence* as result of an extended period of no nuclear construction experience.)

Finon and Staropoli (2001: 179) summarize the unique institutional framework as consisting of four elements: ''*strong political support, a state-owned electricity monopoly endowed with* [substantial] *engineering resources… a highly concentrated*

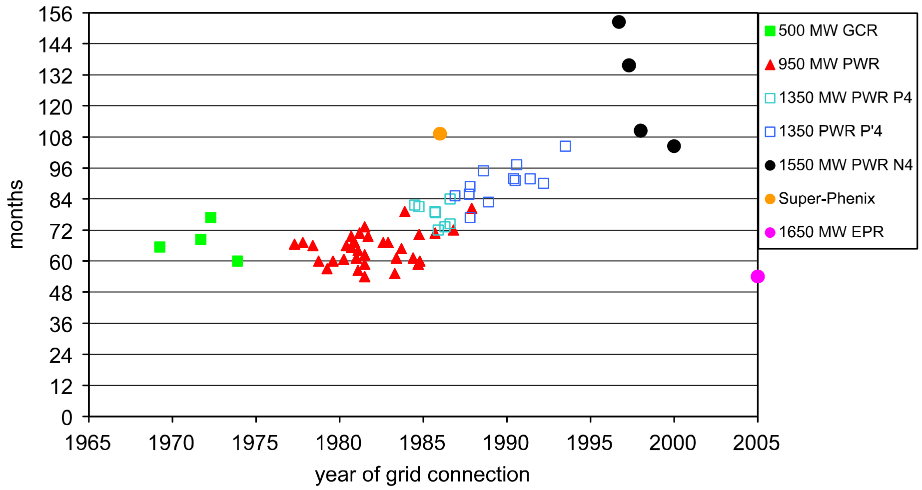


**Fig. 3.** Construction time of French reactors (construction start to first grid-connection, in months). Note in particular the entirely implausible, optimistic projection for the new 1650 MW EPR reactor Flamanville-3 submitted by the French authorities to the IAEA. *Source*: IAEA PRIS Data Base (2009). GCR=graphite gaz reactors.

*electromechanical manufacturing industry* [emerging in the scale-up process], *and an influential R&D public agency*" [the CEA that operated under] *high regulatory stability…and efficient co-ordination resulting from long-term organizational arrangements*." Standardized reactor series, ordered in bulk and profiting from external learning through the use of existing US reactor designs via the Westinghouse license, complemented the unique French nuclear institutional setting.

So "god" and the two "titans" (which controlled the lesser "titans" Framatome and COGEMA) worked "as one"—reducing uncertainty in orders and above all in safety regulations, assuring a consistent technology strategy (e.g., in the increase of unit scales), as well as communicating within the *étatist* system the perceived economic advantages and implementation success in largely internal documents.

The role of coordination fell on a small technocratic elite of state engineers, the so-called *Corps d'État*,[1] whose members continue to be strongly represented within the Ministry of Industry, ÉDF, the CEA, and the nuclear equipment industry. The institutional locus of this elite technocracy was the PEON (1969–1981) Commission (*Commission consultative pour la Production d'Électricité d'origine Nucléaire*), which "*made* [all] *major choices related to nuclear policy, which were subsequently endorsed by the government*" (Finon and Staropoli, 2001: 185).

The single, most noticed measure of success in the French nuclear scale-up is undeniably the construction time, which is short by international standards (see Fig. 3 and Table 1). While a certain increase across the various reactor generations built is evident from the data when measuring months from construction start to first grid connection (IAEA PRIS, 2009), particularly for the later P'4 and especially the N4 reactor types, construction times within the entire program remain quite remarkable. The mean construction time is 76 months, vs. a mean of 108 months in the US reactor sample analyzed by Koomey and Hultman (2007). About half of the French reactors—55% of reactors and 47% of total gross capacity added—have construction times of less than 72 months (6 years). More than 70–76% of reactors, 70% of gross capacity added—have construction times less than 84 months (7 years), which fewer than 35% of all US reactors achieved.

When discussing the importance of standardization in reactor designs as well as short construction times as key technical success factors, special reference needs to be made to ÉDF. This nationalized, powerful utility has often been referred to as "state within the state" by critics (e.g. Gravelaine and O'Dy, 1978). From ÉDF's perspective, cf. Boiteux (2009: 411–412) the success factors are due to (a) size of the order program, (b) standardization (series effects), (c) client engineering of the construction process (i.e., by ÉDF rather than Framatome), and (d) rigorous quality and costs control by ÉDF (that in the words of Boiteux "extends to the beefsteak", i.e. EDF's quality and cost controls even extended to the food offered at the construction sites). Standardization, however, requires continued, dedicated efforts for a technology as complex and potentially consequential as nuclear reactors. And it does need an appropriate institutional setting, independent actors, and strong commitment, which all were in place in the French case. In the words of Boiteux (2009: 411): "*Whenever an engineer had an interesting or even genius* [improvement] *idea either in-house* [ÉDF] *or at Framatome, we said: OK, put it on file, this will be for the next series, but right now, we change nothing*."[2] This again highlights the importance of the *user* or *customer*—the utility—in the successful adoption of a new technology.

MacKerron and Thomas (1986: 11) stress the need for a utility to have the "capacity for technical leadership of nuclear projects and [the] ability to manage and control the various activities

[1] The top graduates of the French elite educational institutions (*Grandes Écoles*) are appointed to engineering "corps" (Mines, Ponts, etc.), forming a small technocratic elite, with just a few hundred members, that self-defines itself to work in the interest of the state rather than of their respective institutions, and that shares common ideological positions and social status whilst maintaining close personal ties. Institutional affiliations are fluid through a system of secondments (*détachements*) or other informal arrangements such as having an office in various institutions/companies. (The pervasiveness of this technocratic network within the French nuclear nexus was recently illustrated by Schneider (2009a, 2009b: 38–40) but awaits further scientific study from the perspective of social network theory. As an illustrative example, the AREVA CEO Anne Lauvergeon is a member of the *Corps de Mines* (established in 1810; its members are recruited mainly from graduates of *École Polytechnique* (*École Normale Supérieure* in Lovergeon's case).

[2] ÉDF CEO Boiteux who was not an engineering graduate (but a world class operations researcher/mathematician), certainly was key in the fight against an engineering culture of continuous tinkering and move to yet a newer reactor generation before the learning possibilities of existing designs had been fully explored. His departure as CEO in 1979 and chairman in 1987 seems to have paved the way towards the erosion of ÉDF's commitment to standardization, caving in to numerous design changes in the P'4 reactors and especially the N4 problem reactor design pushed by the CEA. (A more contemporary example is the MOX (mixed uranium–plutonium oxides) fuel route, again being advanced by the CEA, and facing at best lame opposition by ÉDF.)

involved…requiring skill at managing complexities." Boiteux's emphasis on "client engineering" echoes similar findings from earlier analysis of the economics of US reactors. McCabe (1996) developed a statistical model explaining reactor construction costs by differentiating various learning effects between "principals" (the utility) and "agents" (the architect-engineer/construction firm). He found that learning declined with larger dispersion between principals and agents, and also under the presence of cost uncertainty (inherent in the US contractual arrangements for compensating architect-engineers on a "cost-plus" basis). McCabe also found that in the US, the locus of learning shifted from agents to principals (utilities). From this perspective, ÉDF—by overcoming the principal-agent dichotomy, and by having the institutional capacity with its thousands of well-trained engineers to engineer and manage construction projects as a client—can be considered key in explaining the success in short construction times and moderated cost inflation, at least for the first four order series (CP0 to P4) of 900-MW and the first 1300-MW reactor units.

Conversely, the gradual erosion of ÉDF's determination to standardize (caving in to proposals of numerous design changes in the wake of the "frenchifying" of the Westinghouse design—the P'4 reactor series—and above all to the new N4 reactor design pushed by the CEA), as well as the abrupt slowdown of the expansion program after 1981, paved the way towards a gradual demise of the French success model, as borne out in lengthened construction times and ever higher cost escalation towards the end of the program (cf. Section 4 below).

## 4. Costs

### 4.1. Lifting the veil (data sources)

As mentioned above, reliable data on the costs of the French nuclear program simply were not available before completion of the program, i.e., prior to 2000.

The only economic information widely used within France's nuclear nexus were cost *projections*—in particular, the regularly updated "reference cost" projections by the PEON Commission (succeeded after 1981 by the reference cost projections elaborated by the DIGEC of the Ministry of Industry[3] ). Yet, even if well known to both industry and academics, it is nonetheless interesting to note that these Reference Cost Projections were (with one exception) *de facto* never referred to in the peer-reviewed literature[4] on the costs of French reactors. The internal *Coûts de Référence* of ÉDF were far more closely held, and assumed the quality of a well-guarded industrial secret. As a result, researchers needed to rely on anecdotal evidence (e.g., Thomas, 1988), "grey" literature sources (MacKerron, 1992), or references from outside the country (Finon and Staropoli, 2001). Even knowledgeable scholars like Irvin C. Bupp and Jean-Claude Derian, were forced to conclude in 1978 that French nuclear economics were unknown and would remain unknowable until the French government, perhaps, might someday choose to publish them, which happened only in 2000.

The revolutionary change in cost information disclosure was foreshadowed in a major scenario study (Boisson, 1998) in which ÉDF (1998) disclosed in an annex for the first time its nuclear reference cost projections of levelized costs—albeit only in graphical form. In 1999, Prime Minister Lionel Jospin commissioned a comprehensive study "concerning the economic data of the entire nuclear industry" by three authors Jean-Michel Charpin, Benjamin Dessus and René Pellat. The Charpin–Dessus–Pellat (referred to here as C–D–P, 2000) report and its associated appendices—especially the study by Girard et al. (2000) on the current nuclear installations (*Le Parc Nucléaire Actuel*)—were published within a year. These analyses demonstrate the advantages of France's centralized decision-making and institutional structure, in that it assembled and made available publicly within a year a wealth of economic data that had remained shrouded in mystery for decades. As the study was both commissioned by the French government and also published as official government document it carries special weight.

C–D–P conclude in their preface: "…*in a field where doubt is often expressed as to the accuracy and even trustworthy nature of the information*…[we can] *on* [the] *basis of the contrasting reviews carried out*…*be reasonably confident that our sources are reliable*." This author has no evidence, nor reason, to doubt the conclusions of the C–D–P report's authors. This study therefore draws heavily on the C–D–P report and especially the G–M–T assessment, while drawing also in addition on the Bataille and Galley study published by the technology assessment agency of the French Parliament in 1999 and apparently drawing on the same references and data sources as in the G–M–T study.

To minimize departure for the original data, only minimal adjustments to assure comparability were made. Economic data given in current French Francs (FF) or expressed in constant FF of various years (1995–1998) have been harmonized to a common FF1998 denominator based on the official French GDP deflator. The cost data presented here, therefore, do not include any adjustments for subsequent cost escalation beyond the general rate of inflation. Readers are therefore advised to use caution in interpreting the results when occasionally, for illustration, the data are also expressed in 2008 Euros[5] and 2008 U.S. Dollars. The economic data presented here, refer only to the situation up to 1998, and are *not* an indication of the economics of nuclear reactors ordered or built today. The costs of French nuclear plants now being built or planned cannot be known until they are completed and their data published.

### 4.2. Giga-Watts and Tera-Francs: total costs of the PWR program

The entire nonmilitary costs of the French PWR program are summarized in Table 2. There are some smaller discrepancies ( < 10%) across the various data sources, probably due to different methods of converting to constant FF. However, the numbers given by category agree reasonably well for a program of such a size and complexity. In total the French PWR program cost some 1.5–1.6 trillion ($10^{12}$) FF98 (constant 1998 French Francs). Retaining as a conservative[6] estimate the upper bound of

[3] DIGEC: Direction du Gaz, de l'Électricité et du Charbon, Direction Générale de l'Énergie et des Matières Premières of the Ministry of Industry (var. vols.). A drastic change in attitude became apparent when the author researched the history of the PEON Commission reports in the library/archives of the Ministry of Industry in 2005/2006. The entire staff proved to be extremely courteous and helpful, for which the author expresses his sincere thanks and gratitude.

[4] Even the most knowledgeable French researchers (e.g. Finon and Staropoli, 2001) needed to rely on estimates published outside France by the International Energy Agency, the IEA, to make their point on the comparative favorable economics of the French nuclear program. The only references this author was able to discern that published French reference cost projection data for a given year (but no cost trends) are a peer-reviewed paper by MacKerron (1992, albeit based on an obscure Greenpeace pamphlet [Nectoux, 1991]) and a study in the "grey" scientific literature, the report by Krause and Koomey, 1994. Both presented DIGEC reference cost projection data and, not coincidentally, were published outside France.

[5] Introduced as legal tender on January 1, 2002.

[6] As other indirect subsidies (e.g. military R&D, favorable terms for EDF's financial lending, etc.) to the nuclear program are not included in the available data, the upper bound of the official data in all likelihood represents a minimum cost figure.

**Table 2**
Overview of French PWR program expenditures 1970–2000, low, and reference ranges, in GFF98.
*Source*: G–M–T (2000). Lower values denoted with[a] are from B–G (1999)

| | | | |
|---|---|---|---|
| R&D < 1970 | | 104 | |
| R&D public > 1970 | 57 | 57 | |
| Investments | | | |
| PWR construction | | | |
| PWRs | 460[a] | 480 | |
| End-of-fuel cycle and decommissioning provision | 169 | 169 | |
| **Subtotal capital** | **686** | **810** | |
| Operation expenditures | | | |
| O&M | 400[a] | 402 | |
| Fuel | 419[a] | 431 | |
| **Subtotal operation** | **819** | **833** | |
| Total costs | **1505** | **1643** | **FF98** |
| | 255 | 278 | US$98 |
| | 208 | 227 | Euro2008 |
| | 304 | 332 | US$2008 |
| Levelized costs per kWh | | | |
| 5% discount rate | | **0.22** | **FF98** |
| | | 0.04 | US$98 |
| | | 0.03 | Euro2008 |
| | | 0.05 | US$2008 |

[a] B–G (1999) data. All others from G–M–T (2000).

Table 2, the costs of the French PWR program translate into 230 billion Euros(2008) or 330 billion US$2008.[7]

Total costs (higher range of Table 2) are split between 810 GF98 [billion FF1998] capital expenditures (480 GFF98 investment costs including interest during construction and the remainder being R&D expenditures[8] as well as provisions for the end-of-fuel cycle) and 833 GF98 operating cost expenditures (again about equally split between 402 GF98 operation and maintenance costs and 431 GF98 fuel costs).

These costs of the program of 1.5–1.6 trillion FF98 refer to a total installed PWR capacity of 65.9 GWgross or 63.1 GWnet. Capital costs therefore translate into specific costs of between 10,400 and 12,300 FF/kW (gross) installed, or 10,900–12,800 FF98/kWnet installed. In US$2008, these numbers translate into a range between 2100 US$2008 (lower-bound numbers per kW gross capacity) and 2600 US$2008 (upper-bound values of Table 2 per kW net capacity). As mentioned above, these numbers do *not* include any cost escalation after 1998. They also reflect the average costs of the whole program during 1972–98, although, as will be shown below, actual costs trended upwards during that period.

The above capital expenditures do not include investments in the fuel cycle facilities, whose amortization and finance are reflected in the fuel costs in Table 2. Bataille and Galley (1999) summarize those fuel-cycle investments at 122 billion current FF, which translates into 169 GF98. About half of these investments relate to the fuel cycle (enrichment, reprocessing, etc.), capacity of the French PWR program (some 85 GF98) with the remainder being covered by foreign clients, for contractual use of French fuel cycle capacity.

Also excluded are expenditures related to the unsuccessful fast breeder reactor Superphénix (effectively more an R&D project than a commercial investment). To put its numbers into perspective: Schneider (2009a: 77) presents French estimates of some 65 GFF (presumably in current Francs) total lifecycle costs of the 1.2-GW fast breeder reactor. With the benefit of hindsight, the contested decision to move to reprocessing (and to stay in it for the time—one of the conclusions of the C–D–P report) seems to make eminently more economic sense than the French fast breeder program.

### 4.3. *Costs over time (1970–2000)*

#### 4.3.1. *Total costs per category*

Annual and cumulative expenditures over time are shown in Figs. 4 and 5.

Since the early 1980s, expenditures per year are roughly 65 GF98 per year, or about 1 FF98 per W installed capacity, or about 0.16 FF98 per kWh generated (at the completion of the program when it produced 400 TWh/yr). Evidently, as the program was completed, the structure of these expenditures shifted from investment to operating expenditures.

Using a real annual discount rate of 5%, the total PWR costs translate into levelized costs of 0.22 FF98 per kWh produced, or some 31 Euro2008 or 45 US$2008 per MWh—again not considering any cost escalation since 1998, and averaging over the entire program. (Levelized costs vary between 0.2 and 0.24 FF98/kWh when deploying a real annual discount rate of 10% and 3%, respectively.)

That averaging over the entire 26-year program, however, masks decisive differences in the economics over time and across different reactors. Unfortunately, no cost information by reactor is available to perform an analysis comparable to the formidable study of Koomey and Hultman (2007) for the US. Given the evidence of lengthened construction time discussed above (even compared with the worse experience in other countries, notably the US), one should expect a substantial escalation in real construction costs over time. These are analyzed further in the next section.

#### 4.3.2. *"Forgetting by doing"? Real escalation in reactor investment costs*

Although the available data do not present investments costs per individual reactor or per specific reactor generation, one nonetheless can infer from the annual construction expenditure (see Fig. 4) some general and specific trends over time based on some simple, plausible arithmetic.

*4.3.2.1. Estimation method.* The method is simple: Construction investments are constrained by construction duration, over which expenditures follow typically a triangular distribution. Construction and completion dates are available from the IAEA PRIS data base, some characteristic time profiles of expenditures have been found in ÉDF's reference cost projections (ÉDF CdR, 1976)) as well as an actual example (Tricastin, cf. PEON, 1979) that are approximated by four models. Of these, two are realistic; the others, describing linear and inverse construction expenditure patterns, are useful only for sensitivity analysis. The resulting construction expenditure profiles are summarized in Fig. 6. Combining three alternative definitions of construction duration—time from construction start to: (a) first criticality, (b) first grid connection, or (c) commercial operation (as reported by IAEA PRIS)—with our four models of expenditure profiles allows us to allocate the actual construction expenditures to the sum of the fractional MW

[7] 2008 values given here are only indicative as there is no longer an official exchange rate between the French Franc and the US$. The 1998 US$ values assume an exchange rate of 5.9 FF/US$ (mean annual exchange rate in 1998). Over the period 1990–2001 this exchange rate has varied between 5.0 and 5.9 FF/US$, so the total costs expressed in US$ could also be 18% higher (329 billion US$1995 using the 1995 exchange rate of 5 FF/US$). Using a different exchange rate however does not affect the calculated levelized costs of 0.04 US$98/kWh at the significance level of the numbers presented.

[8] Public-sector R&D (basically government funding for the CEA) only. These expenditures are treated as knowledge capital investments here. Private R&D by EDF and the nuclear industry are not available separately but are included in the other expenditure items like investments, O&M and fuel costs (G–M–T-2000: 133). Also, pre-1970 R&D expenditures are included in Table 2 and the numbers discussed above. Arguably, without these prior R&D and associated buildup of nuclear knowledge capital, the post-1970 PWR program could not have been implemented. These pre-1970 R&D expenditures are excluded from the lower-bound values given in Table 2.

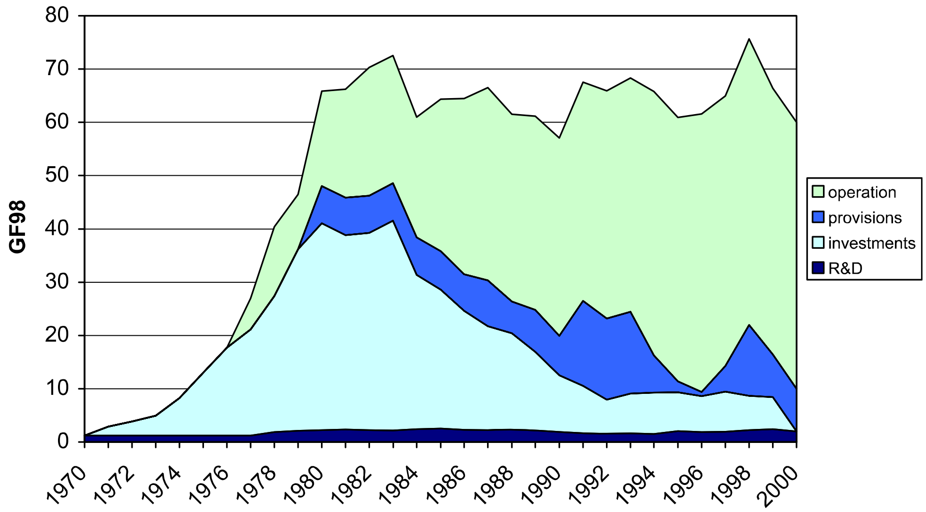


**Fig. 4.** Expenditures per year for French PWR program 1970–2000 in Billion French Francs1998 (GFF98), by major expenditure type. *Source*: G–M–T (2000).

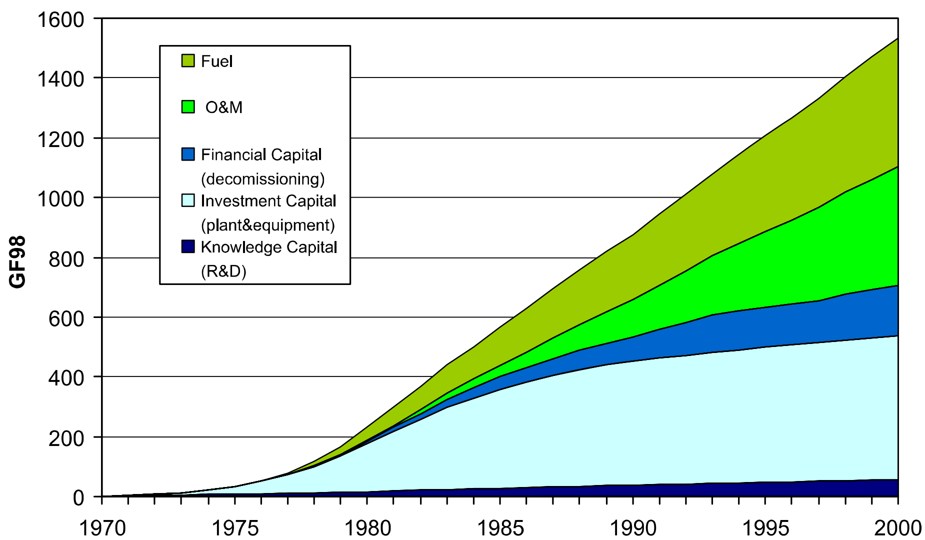


**Fig. 5.** Cumulative expenditure of the French PWR program 1970–2000 in Billion French Francs1998 (GFF98, conservative range of estimates available) (see also Table 2).

constructed in a particular year, yielding the average specific construction costs per kW constructed over time. We perform this calculation for two data sets of construction expenditures based on the data given in Girard et al. (2000: 125) and by Bataille and Galley (1999: Tableau Investissements d'ÉDF). These data sources are summarized in Fig. 7. Altogether 24 (three definitions of construction duration *times* four scenarios of expenditures profiles *times* 2 data sets of total investments over time) scenarios of annual costs per kW have been calculated for the "best guess" cost estimates as well as the two uncertainty ranges ("uncertainty-1", and min/max of all scenarios). As it turned out from this extensive sensitivity analysis the assumed construction expenditure pattern over time hardly influences the uncertainties of the calculated specific construction costs. The most determining variable is construction duration, as explored by the three scenarios outlined above (Table 3).

*4.3.2.2. Results.* The results are summarized in Fig. 8 showing "best guess" model outputs, as well as two uncertainty ranges, of which only the uncertainty−1 range is considered "reasonable": the larger uncertainty range shown in Fig. 8 implies the combination of quite implausible assumptions,[9] so it is reported here only for completeness.

The method employed allows a reasonable approximation between 1974 and 1990, when on average at least a total of 1 GW of nuclear capacity was under construction. Before and after that period, too few reactors were constructed to report meaningful yearly results, leaving only 0.1–0.2 GW in each year's denominator, so a simple average of the pre-1974 years as well as of the post-1990 years is reported in Fig. 8, respectively pegged somewhat arbitrarily to the years 1972 and 1995. These two constructed points refer to the average costs of the first CP0[10] reactors and of the last N4 reactors.

[9] For example: Combining end of construction expenditures with first criticality date (reached for three N4 reactors between 1996 and 1998 and the last in 1999, whilst the data sources report actual construction expenditures at least to 1998) combined with a linear expenditure profile.

[10] Assuming construction start as the beginning of construction expenditures yields implausibly high costs for these first reactors. The "best guess" and uncertainty−1 results reported in Fig. 8 assume therefore that expenditures started in fact 1 year before the officially reported construction start for the CP0 series. The larger uncertainty range results relax this plausible assumption.

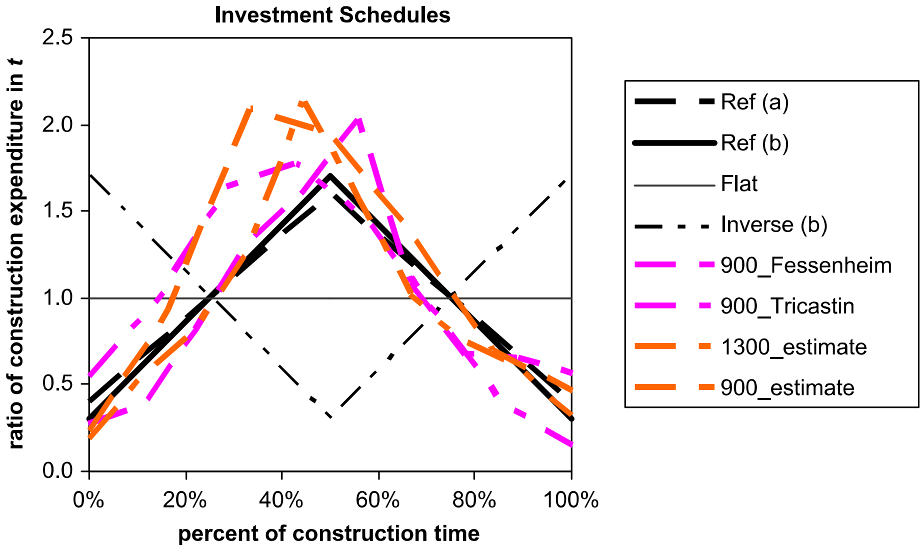


**Fig. 6.** Four illustrative profiles of construction expenditures (ratios of actual annual expenditure over the average annualized expenditures over the entire construction period, i.e. expenditure pattern scenario compared to a flat expenditure pattern) over time (in percent of total elapsed construction time) used in modeling specific construction costs. Modeled scenarios (black) compared to actual construction expenditure profiles (magenta) of the Fessenheim and Tricastin 900 MW reactors (PEON, 1979) and ÉDF CdR estimates for a typical 900 and 1300 MW model reactor (orange). The triangular higher-peak model (Ref(b) bold black line) is used to derive "best guess" annual average construction cost estimates for the reactors built in a particular year from the aggregated construction expenditure curve (cf. Fig. 7). For further explanation see text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

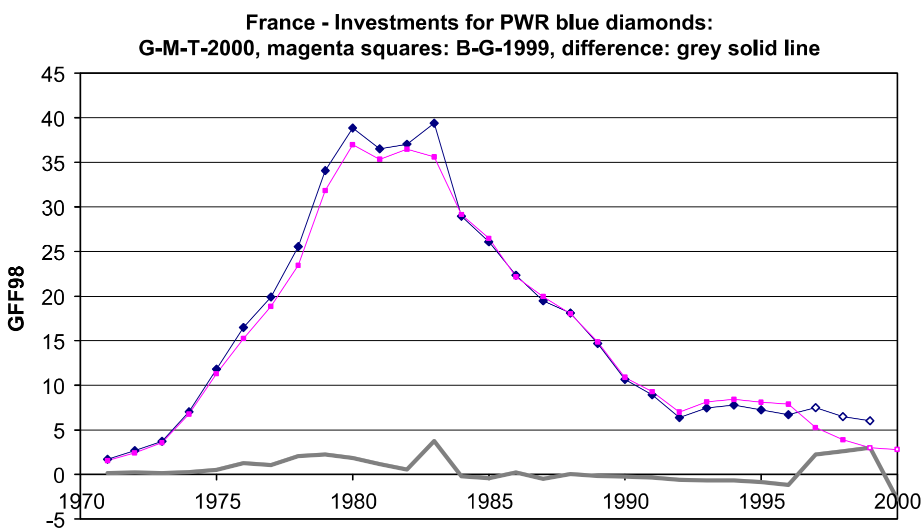


**Fig. 7.** Comparison of two reported PWR construction expenditures (G–M–T (2000) vs. B–G (1999), both apparently drawing on the same original internal ÉDF data) and their difference in GFF98. Open symbols indicate extrapolations for incomplete reporting on from the program grand totals of 470 GF98 from G–M–T (2000:125) bringing the final grand total to 480 GF98.

**Table 3**
Taxonomy of investment cost scenarios calculated.

| | | "Best guess" | Uncertainty-1 | Min/max all 24 scenarios |
|---|---|---|---|---|
| Data source | G–M–T (2000) | x | x | x |
| | B–G (1999) | | x | x |
| Dates defining construction duration | | | | |
| Construction to start of | | | | |
| | Criticality | | x | x |
| | Grid-connection | x | x | x |
| | Comm. operation | | | x |
| Expenditure profile model | | | | |
| | Reference model ref (b) (peaked triangular) | x | x | x |
| | Ref (a) (triangular) | | | x |
| | Flat (constant) | | | x |
| | Inverse b (inverse) | | | x |

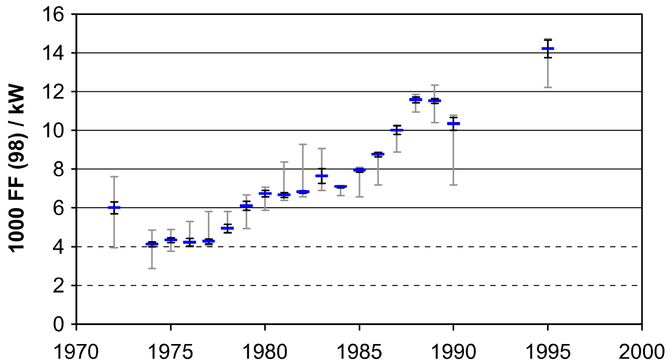


**Fig. 8.** Specific investment costs of French PWRs (1000 FF98 per kW yearly averages) over time, best guess model (blue) estimates and two uncertainty ranges (black and grey). The largest uncertainty range refers to minima and maxima of all cost estimation scenarios calculated, respectively, which do not necessarily combine plausible scenario assumptions and need therefore to be considered as extremes of a sensitivity analysis. Values plotted for 1972 and 1995 are averages for the entire period before 1974 and after 1990, respectively. For numerical values see Appendix Table A1. (For comparison: the exchange rate in 1998 was 5.9 FF/US$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Despite some shortcomings of the analysis, the results illustrate clearly the substantial real cost escalation of the French PWR program. Between 1974 and 1984, specific real investment costs increased from some 4200–7000 FF98/kW (gross capacity), or by some 5% per annum. Between 1984 and 1990, costs escalated from some 7000 to 10,000 FF98/kW, or by some 6% per annum. For the last reactors, the "entirely French design" N4 series, the inferred construction costs are about another 45 percent higher (14,500 FF98/kW "best guess" model estimate), yielding a cost escalation of about a factor 3.5 (14,500/4200) between 1974 and the post 1990 period and of a factor of 2.4 between the years 1974 and 1990.

The cost allocation model also allows one to infer reactor-specific construction costs, albeit at the price of an additional uncertainty margin. Average costs per year over all reactors (Fig. 8 and Appendix Table A1) can be allocated to individual reactors on basis of their respective fractional shares of capacity constructed in that year based on the various models of construction expenditures explained above (cf. Fig. 6). The sum over all construction years of the thus inferred yearly average costs per fractional capacity constructed over the three construction duration definitions (and the two expenditure data series) yields a total construction cost estimate per reactor under the (constraining) assumptions that construction costs over all reactors constructed in a particular year can be averaged. Fig. 9 (and Appendix Table A2) presents the results of this exercise. Due the additional uncertainties involved in these model calculations, it seems appropriate to report only the larger min/max−2 values of uncertainty in Fig. 9 and in the Annex Table 2 (which is also recommended for any subsequent further statistical analyses by interested researchers). The reactor-specific construction costs estimates display a comparable upward dynamic as the average yearly costs shown in Fig. 8 above. (Note however the different timing in the two graphics: Fig. 8 refers to yearly averages of reactors *being constructed* (but not completed) in that year, whereas Fig. 9 needs to peg reactor-specific costs to a discrete time step, for which we have chosen the date of first criticality as perhaps best indicator of construction completion). Quite naturally the dispersion of cost data is larger than in the yearly averages shown above.

The difference between the most costly and cheapest reactors built (Civaux-2 and Bugey-4, respectively) is a factor of 4.5 (20,228/4538 FF98/kW using best-guess model estimates), a factor difference that becomes reduced to a range of 2.6 and 2.3, respectively considering the cost dispersion between the second and third most expensive/cheap reactor pairs, respectively. This suggest, that above conclusion of a factor 3.5 increase in construction costs between 1974 and post 1990 is likely to be heavily influenced by the extreme of the phenomenal cost overruns of the Civaux-2 N4 reactor, whose estimates are however affected by a considerable margin of uncertainty. Excluding that extreme observation, and averaging costs per reactor generation, the cost escalation is more moderate, albeit still substantial: an increase from 4635 FF98/kW (average of the 4 CP0 reactors Bugey 2–5[11]) to 10,972 FF98/kW (average for the 3 N4 reactors excluding Civaux-2), i.e. of about a factor of 2.4. While this escalation is more moderate compared to the experience in other countries, most notably the US, it remains nonetheless both substantial and highly significant considering the nuclear scale-up in France is the example with the arguably most favorable institutional environment (central planning, no regulatory uncertainty) for nuclear power.

This observed real cost escalation is quite robust against the data and model uncertainties that can be explored. The largest uncertainties arise instead from constraining the available data sample. The largest influence arises in the case when the high costs of the last N4 reactors completed (especially Civaux-2) are excluded in the considerations, and to a lesser extent also if the sample of cheap CP0 reactors is either constrained to the cheapest reactors completed or whether one also includes the more expensive first two Fessenheim reactors. Based an extensive sensitivity analyses with both cost escalation data (Figs. 8 and 9), their corresponding uncertainty ranges (Appendix Tables A1 and A2), and a range of sample size manipulations, we conclude with a *minimum cost escalation* estimate for the French PWR program of a factor 2.4 with an uncertainty range of a factor between 2.2 and 2.6. We refrain here to report the results of the regression equations on annual cost escalations. This simply in order not to suggest that the cost increases are an quasi "autonomous" time trend (akin to inflation), as alas frequently assumed in econometric analyses. The significant cost escalation needs first of all be understood as the outcome of deliberate decisions concerning reactor scale, design, deviations from the tested Westinghouse license through "frenchifying" reactor components, and also the significant scale-back in the expansion program after 1980 rather than an exogenously given inflationary time trend.

Above discussed cost escalation is far above what would be expected just from longer construction times.[12] An in-depth analysis for this cost escalation awaits further detailed research (and the publication of official reactor-specific construction costs data), but the main reasons have been already alluded to above: loss of the cost-dampening effects from standardization, partly due to upscaling to 1300 MW, but especially in the "frenchifying" of the tested Westinghouse design (as evidenced in the differences between the P4 and the P'4 reactor series); a certain "stretching" in the construction schedules after 1981 to maintain human and industrial knowledge capital during the significant scale-back of the expansion program as a result of built over-capacity (that resulted from over-bullish demand growth forecasts); and above all, the unsuccessful attempt to introduce a radically new, entirely French design towards the end of the

[11] Excluding the first two CP0 reactors Fessenheim 1 and 2, whose higher costs either indicate start-up difficulties of the scale-up program or conversely a weak learning effect for the subsequent later CP0 reactors at the Bugey site.

[12] Compared to the US accrued interest during lengthened construction time exerts a smaller influence in the French case as only a fraction of investments have not been auto-financed by ÉDF (read: the French ratepayer).

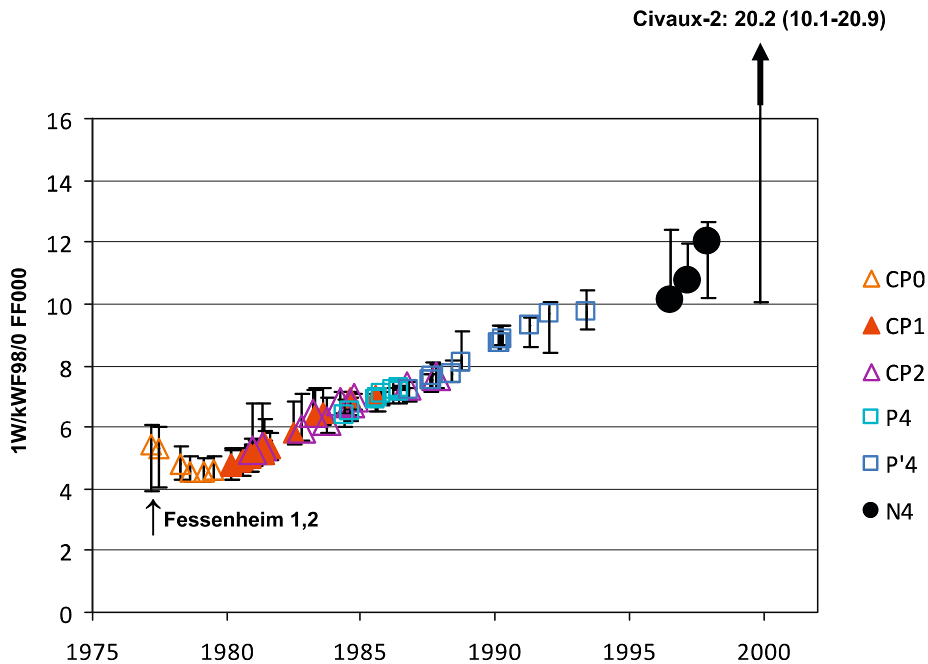


**Fig. 9.** Inferred specific reactor construction costs (1000 FF98/kW) per French PWR reactor sorted by reactor type and completion date (year of first criticality), best guess and min/max−2 uncertainty ranges of estimates. For numerical data underlying the graph see Appendix Table A2. (For comparison: the exchange rate in 1998 was 5.9 FF/US$.)

program (the N4 reactors) that did not allow any learning spillovers in design or construction.

The reactor design changes undeniably improved safety features (Thomas (1988) and Bataille and Birraux (2003), who compare the N4 with the EPR reactor). But that was never a prime motivation for the changes in design and is therefore unlikely to be a significant factor in the cost escalation compared to the much more drastic and cost-consequential design changes aimed at improving reactor economics, higher domestic value added for the nuclear industry, and export market potentials.[13] These endogeneous non-safety drivers of design changes can be summarized simply as: ever larger scale and more output (the interest of the ÉDF), more French equipment and components (the interest of the nuclear equipment industry), and finally technological leadership (the interest of the CEA). In the view of the author, these endogeneous drivers and the radical design changes they caused need to be analyzed as primary causes for the significant real cost escalation, with the influence of improved safety features likely to be small.

#### 4.3.3. *"Against all odds": stability in operation costs*

Available data only allow us to analyze the evolution of average operating costs across all reactors "on-grid" over time. The trends are summarized in Fig. 10.

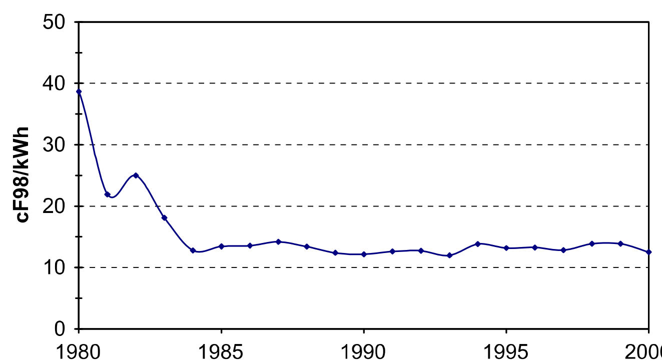


**Fig. 10.** Average operating costs (including fuel costs) (in centimes FF98 per kWh) of French PWR fleet 1980–2000. (For comparison: The exchange rate in 1998 was 5.9 FF/US$.)

Even if not exhibiting the classical features of a "learning" or "experience" curve, the stability in specific operating costs is quite a remarkable achievement considering the increasing need for load modulation in a system in which a base load technology such as nuclear supplies 80% electricity. After an initial learning (which is more an artifact of a program rapidly connecting large number of reactors to the grid than testimony of classical "learning-by-doing"), i.e., since 1984, operating costs have remained essentially flat, averaging 0.13 FF98 (13 centimes, cFF98) per kWh produced. To put this number into perspective: operating costs equal some 18 Euro2008 per MWh produced, or some 30 US$2008/MWh: not exactly "too cheap to meter", but certainly very competitive, especially in comparison with new technologies entering the market (including new generations of nuclear reactors).

The stability in operating costs is also notable beyond the odds of load modulation. A second potential cost escalation looms: the downside of the standardization in French reactor designs, which in case of generic design flaws require costly retrofits on all

[13] CEA's ultimate triumph (against ÉDF's opposition) was anticipated to be the entirely French N4 reactor design. While the rationale given was easier export (the Westinghouse license initially required US government approval for exports) as well as improved safety features (reflecting the lessons from the US Three Mile Island accident), an institutional interpretation appears more plausible: the CEA wanted to reassert its role as major national technology developer, akin to the 1960s. As it turned out later, the decision to develop and build the N4 reactor was the most problematic of the entire French PWR program: the new reactor faced numerous technical difficulties (cf. MacLachlan, 1991), substantial delays, and by French standards, prohibitive costs overruns. Not a single N4 reactor was exported. All in all, France exported 9 reactors to 4 countries—all of the original 900-MW first-generation Westinghouse license type (Marignac et al., 2008: 25).

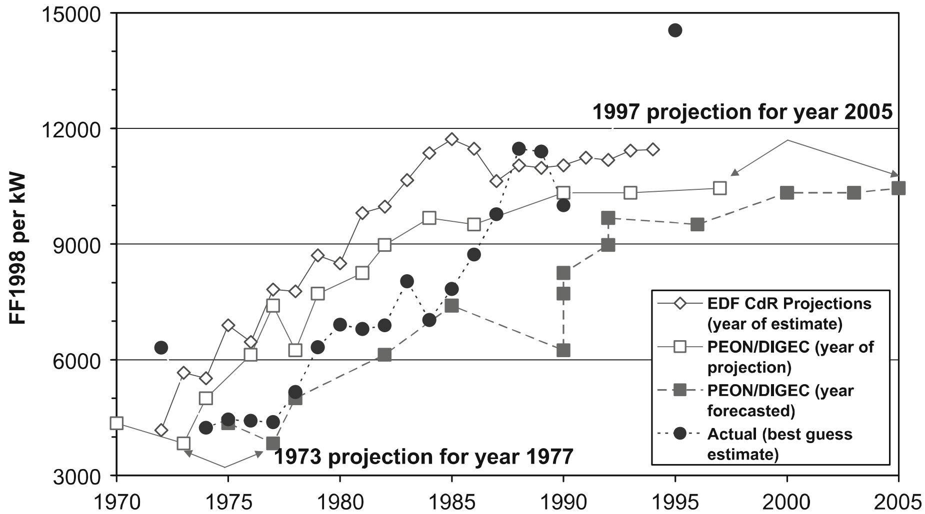


**Fig. 11.** Cost projections (FF98 per kW installed) by ÉDF and PEON/DIGEC versus estimated actual costs (best guess model of average yearly construction costs, cf. Fig. 8).

reactors affected of a particular series (as was actually required in a number of cases, e.g., for the reactor "*couvercles*" [lids]). Nonetheless, even with expensive retrofits, have operating costs remained flat.[14] The French experience confirms the economic history of nuclear in other countries as well: Once initial high investment costs are ignored (e.g., written off), operating costs are low, adding a powerful economic incentive for life extensions of the existing reactor fleet.

## 5. Actual versus projected costs

It is an old adage in technological forecasting that "cost projections are always wrong". The nuclear industry has contributed at least proportionately to this conclusion (see e.g., Cohn, 1997). Critics have repeatedly highlighted concerns about the strategic misuse of cost forecasts that were set extremely low to justify investments, with decision-makers, typically utility managers, consequently being "locked-in" to ever-escalating costs. The following analysis helps us to contrast forecasts and reality with the benefit of hindsight (Fig. 11).

Forecasting the costs of energy technologies has always been a "core business" of government and industry alike in France ever since the reports of the PEON Commission in the 1960s. Their "reference cost" projections formed a central part of the regular Commission reports until their last one released in 1979. Subsequently, the job of projecting was taken over by the DIGEC department within the Ministry of Industry that followed closely the PEON template. Also ÉDF made its own internal reference cost projections, which were kept secret (but nonetheless leaked out, e.g., to this author) until a change of strategy and disclosure in 1998. Comparing actual costs with projections is however not so straightforward. Whilst the date of publication of a particular projection is a precise number, the forecasted year to which a projection applies is used rather loosely in the reports. Often, future dates are given as ranges, or a particular forecasting horizon (e.g., 1990) is retained in subsequent annual projection updates, resulting in ranges of projections for a particular year, depending on the year the forecast was made. Nonetheless as always, a comparison of projections with actual developments yields interesting insights.

One conclusion, perhaps surprising for many, is that with the exception of the last N4 reactors, the cost projections (particularly from later years closer to the forecasting horizon)[15] were pretty accurate. Both PEON/DIGEC's and ÉDF's projections also reflected quite accurately the real cost escalation in reactor investments from the above *ex post* expenditure analysis. However, they reflected the observed real cost escalation only with a *substantial lag*. ÉDF (being closer to the realities "on the ground") was faster in adjusting its reference costs compared to the PEON Commission, and thus turned out to be the more astute forecaster, even if only for an "in-house" audience. Whatever internal discussions might have occurred about the implications of the real cost escalation for ordering strategy have not yet been revealed.

The projections also bear witness to the economic expectations of the actors. Declining trends indicate the cost-reducing expectations (however never realized) of upscaling to the 1300-MW reactor series, and also, by the mid-1980s, the unfounded hopes of cost savings from the N4 reactor design. It is particularly noteworthy that while cost projections in the 1970s and 1980s reflected cost escalation trends well from actual experience (albeit with a delay), they no longer did so in the 1990s, when the substantial cost overruns and difficulties of the N4 reactor design must have been apparent to all insiders, yet were not visible in the cost projections. Apparently, the projections no longer served their original purpose—to communicate the benefits of the nuclear program within France's technocratic elite—but were rather instrumentalized—so as not to add insult to injury—to communicate an economic success story whilst distracting from the difficulties encountered with the problem N4 reactors. Ever since, the cost projections have further lost their credibility and usefulness in public discourse or in decision-making.[16]

[14] One operation cost lowering effect is certainly the higher burn-up rates achieved, lengthening the operation period between two refueling stops (to some 22 months). Unplanned outages have also decreased with increasing accumulation of operating experience, albeit a detailed account of factors determining operation costs remains unavailable to date.

[15] For instance, EDFs CdR projection made in 1976 projected nuclear investment costs for the year 1985 below 6500 FF98/kW, but two years later, the 1978 CdR, again projecting for 1985, foresaw some 7800 FF98/kW, in good agreement to our "best guess" *ex post* estimate of average construction costs in 1985–7833 FF98/kW.

[16] In an almost farcical endpoint in decline of forecasting culture, the latest reference cost projections (DGEC, 2008) do not even contain any concrete cost

## 6. Summary and lessons for the future

The ambitious French PWR expansion program is legitimately considered the most successful scaling-up of a complex, large-scale technology in the recent history of industrialized countries. This paper has argued that above all, the reasons for this success lay in a unique institutional setting allowing centralized decision-making, regulatory stability, dedicated efforts for standardized reactor designs (which could long profit from knowledge spillovers via the Westinghouse license), and a powerful nationalized utility, ÉDF, whose substantial in-house engineering resources enabled it to act as principal *and* agent of reactor construction simultaneously.

As a result, the scaleup of PWRs was both substantial (nuclear now produces 76% of all electricity generated in France, and ÉDF has managed to operate reactors in load modulation mode), rapid (50 GW installed within 10 years, with mean construction times generally much faster than in other countries such as the US or Germany) and systemic in terms of the complete development of a concentrated national nuclear equipment industry and fuel cycle.

The economic assessment of this scaleup yields a more differentiated picture.

Despite a most favorable setting, the French PWR program exhibited substantial real cost escalation. This increase is substantially lower than in other countries, most notably the US. Given the almost identical technological characteristics of reactors in the US compared to France, Fig. 12 powerfully illustrates the impacts of different institutional settings on the economics of scaling-up large-scale, complex technologies. The "central planning" model with its regulatory stability and unified, nationalized, technically skilled principal-agent (EDF) appears economically more successful, with substantial but moderated real cost escalation, than the more decentralized, market-oriented, but regulatorily uncertain (and multi-layered, i.e. state and federal) US system. Nonetheless, despite more moderate cost escalation, the French experience nonetheless raises a number of fundamental issues worth considering in a climate-constrained world.

First, while the nuclear industry is often quick to point at public opposition and regulatory uncertainty as reasons for real cost escalation, it may be more productive to start asking whether these trends are not intrinsic to the very nature of the technology itself: large-scale, lumpy, and requiring a formidable ability to manage complexity in both construction and operation. These intrinsic characteristics of the technology limit essentially all classical mechanisms of cost improvements—standardization, large series, and a large number of quasi-identical experiences that can lead to technological learning and ultimate cost reductions—except one: increases in unit size, i.e., economies of scale. In the history of steam electricity generation, these indeed led initially to substantial cost reductions, but after the late 1960s that option has failed invariably due to continued design changes (leading to higher material requirements per kW – the current EPR design being the most "heavy") and also increases in technological complexity.

Second, whilst reactors' real construction costs increased steadily, their *operating* costs remained low and flat in France, as well as for many reactors elsewhere. Perhaps the nuclear "valley of death" is its inherently high investment costs and their tendency to rise beyond economically viable levels. Perhaps new

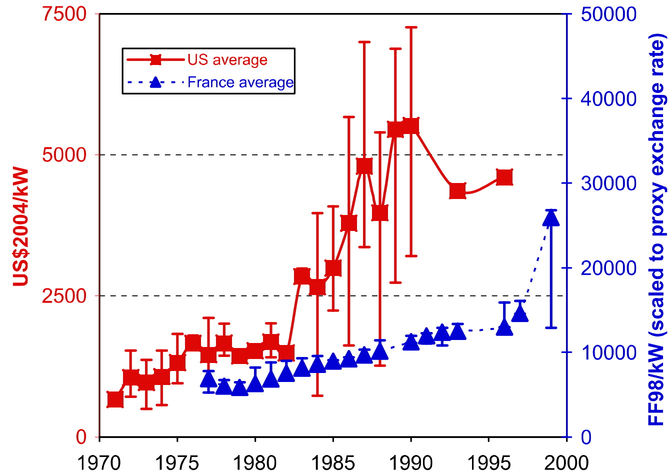


**Fig. 12.** Comparison of French (FF98/kW, this study) and US (US$94/kW, Koomey and Hultman, 2007) nuclear construction costs, average and min/max per reactor completion year (year of entering into service in US, year of first criticality in France, cf. Fig. 9). The different metrics are scaled in proportion to yield an approximately correct exchange rate, but the customary caveats of technology cost comparisons across countries and different currencies apply (adopting alternative exchange rates might increase the French costs in US$ terms by $<20\%$). In both data sets, average costs refer to the specific construction costs of all reactors completed in that particular year. Min/max values show the respective highest/lowest reactor in the US (therefore there are no uncertainty bands for those years where only a single reactor was completed) and the min/max$-2$ uncertainty ranges for the inferred reactor specific cost data in France (see text for explanation).

institutional configurations that separate centralized reactor construction from decentralized operation should be explored, if indeed a nuclear expansion is deemed in the public interest to respond to climate concerns. ÉDF's success in combining principal and agent in the construction process could be at the core of such considerations (even if that model might no longer be viable even in France due to knowledge obsolescence). Conversely, this logic may suggest that competitive nuclear power is unlikely to be achieved in a private free market, which instead is tending to produce the rapid innovations that now competitively challenge nuclear power.

Thirdly, this case-study provides valuable lessons for energy technology and climate policy analysts. Cost projections of novel technologies are an inherent element in any climate change policy analysis. This case-study has reconfirmed the conclusion of Koomey and Hultman (2007) that projections of the future need to be grounded much more firmly within the historical observational space, requiring much more careful arguments and logic in scenario design and model runs before suggesting "robust" or "optimal" climate stabilization pathways. Again, agreeing with Koomey and Hultman (2007), detailed justification needs to be provided in case assumptions differ radically from historical experience.[17]

These findings also suggest a need for in-depth sensitivity analysis across a much wider range of technological cost uncertainties. Perhaps climate policy analysis could begin by embracing in sensitivity analyses the engineering rule of thumb that large-scale infrastructure construction projects trend to always cost 2–3 times the original estimate. Nuclear is not the only example of a large-scale, complex technology that might be subject to this engineering rule: coal-based integrated gasification

(*footnote continued*)
numbers, comparing options instead through relative indices with nuclear set as 100.

[17] For instance, the substantial cost declines along a learning curve for nuclear reactors assumed by Kouvaritakis et al. (2000) as being counterfactual to even the most successful nuclear scale-up are certainly both biased scenario modeling as well as bad policy advice.

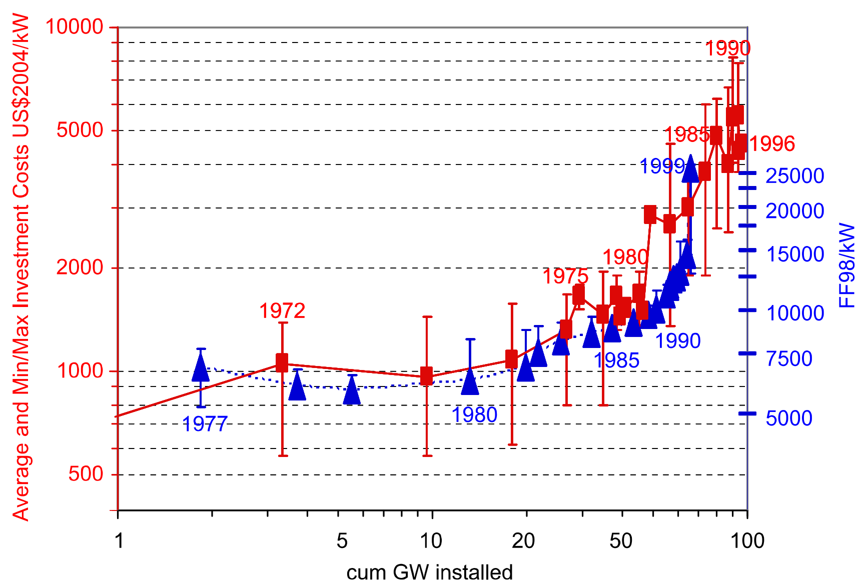


**Fig. 13.** Average and min/max reactor construction costs per year of completion date (cf. Fig. 12 above) for US and France versus cumulative capacity completed.

combined cycles with carbon capture and sequestration (or very large-scale solar plants in desert areas) would be prime candidates as well.

Lastly, the French nuclear case has also demonstrated the limits of the learning paradigm: the assumption that costs invariably decrease with accumulated technology deployment. The French example serves as a useful reminder of the limits of the generalizability of simplistic learning/experience curve models. Not only do nuclear reactors across all countries with significant programs invariably exhibit negative learning, i.e., cost increase rather than decline, but the pattern is also quite variable, defying approximations by simple learning-curve models, as shown in Fig. 13.

First of all, Fig. 13 provides a useful reminder on the dangers of "logarithmic compression" in the customary double log learning curve representations. Despite the learning curve metaphor is clearly not applicable in the case of nuclear in both the US and France illustrating the limits of simplistic learning curve assumptions in technology studies and policy models, the model nonetheless allows an additional insight. The *rhythm* (as opposed to the different rates and extent) of cost escalation between the two countries appears strikingly similar. Initially, cost escalations are positive, but modest until a threshold value of some 20 GW installed capacity is reached, followed by a phase of accelerated cost escalation to another threshold level at some 40–50 GW, beyond which cost escalation simply skyrockets. At this stage above observation remains entirely conjectural. Further evidence from more country studies (and disclosure of reactor specific costs data for France to improve upon the estimates presented here) are needed before above conjecture can be moved to the status of a hypothesis and explanatory factors explored. However, it seems not implausible to speculate about the existence of non-linear threshold effects in the economics of large-scale complex technology systems that however in the case of nuclear (as opposed to ITC) work in the opposite direction (i.e. costs increase rather than decrease).

In symmetry to the often evoked "learning-by-doing" phenomenon, there appears not only to be "forgetting by not doing"[18] (Rosegger, 1991) but also "*forgetting by doing*", suggesting that technology learning possibilities are not only structured by the actors and institutional settings involved, but are also a fundamental characteristic of technologies themselves.

In the case of nuclear, a theoretical framework explaining this negative learning was discussed by Lovins (1986: 17–21) who referred to the underlying model as Bupp–Derian–Komanoff–Taylor hypothesis. In essence, the model suggests that with increasing application ("doing"), the complexity of the technology inevitably increases leading to inherent cost escalation trends that limit or reverse "learning" (cost reduction) possibilities. In other words, technology scale-up can lead to an inevitable increase in *systems complexity* (in the case of nuclear, full fuel cycle management, load-following operation mode, and increasing safety standards as operation experience [and unanticipated problems] are accumulating) that translates into real-cost

**Table A1**
Average specific French nuclear reactor construction costs inferred from annual expenditures. Best guess and min/max values for two uncertainty ranges (in 1000 FF98 per kW).

| 1000 FF98/kW | Best guess | Min-1 | Max-1 | Min-2 | Max-2 |
|---|---|---|---|---|---|
| Pre-1973 avg | 6.31 | 5.69 | 6.31 | 3.94 | 7.61 |
| 1974 | 4.23 | 4.01 | 4.23 | 2.88 | 4.84 |
| 1975 | 4.45 | 4.21 | 4.45 | 3.75 | 4.89 |
| 1976 | 4.42 | 4.04 | 4.42 | 4.01 | 5.30 |
| 1977 | 4.38 | 4.14 | 4.38 | 4.07 | 5.82 |
| 1978 | 5.16 | 4.72 | 5.16 | 4.70 | 5.83 |
| 1979 | 6.32 | 5.88 | 6.32 | 4.93 | 6.67 |
| 1980 | 6.91 | 6.57 | 6.91 | 5.88 | 7.07 |
| 1981 | 6.80 | 6.54 | 6.80 | 6.39 | 8.37 |
| 1982 | 6.89 | 6.74 | 6.89 | 6.58 | 9.28 |
| 1983 | 8.03 | 7.27 | 8.04 | 6.90 | 9.05 |
| 1984 | 7.03 | 7.03 | 7.13 | 6.63 | 7.14 |
| 1985 | 7.83 | 7.83 | 8.03 | 6.58 | 8.10 |
| 1986 | 8.73 | 8.65 | 8.85 | 7.19 | 8.89 |
| 1987 | 9.78 | 9.78 | 10.23 | 8.88 | 10.26 |
| 1988 | 11.47 | 11.43 | 11.72 | 10.93 | 11.83 |
| 1989 | 11.40 | 11.40 | 11.65 | 10.39 | 12.35 |
| 1990 | 10.01 | 10.01 | 10.66 | 7.19 | 10.79 |
| Post 1990 average | 14.54 | 13.76 | 14.68 | 12.22 | 14.74 |

[18] Cost escalation as a result of knowledge depreciation/obsolescence and/or erosion institutional capability.

**Table A2**
Inferred investment costs per reactor (in billion FF98), sorted by reactor type and construction completion (date of first criticality), best guess and min/max-2 values of estimate. For estimation method see text.

| PPL | Type | MW | Crit. date | Investment costs per reactor (billion FF98) | | |
|---|---|---|---|---|---|---|
| | | | | Best guess | Min-2 | Max-2 |
| Fessenheim 1 | CP0 | 920 | 3/7/1977 | 5.0 | 3.6 | 5.6 |
| Fessenheim 2 | CP0 | 920 | 6/27/1977 | 4.9 | 3.7 | 5.5 |
| Bugey 2 | CP0 | 945 | 4/20/1978 | 4.6 | 4.1 | 5.1 |
| Bugey 3 | CP0 | 945 | 8/31/1978 | 4.3 | 4.0 | 4.8 |
| Bugey 4 | CP0 | 917 | 2/17/1979 | 4.2 | 3.9 | 4.6 |
| Bugey 5 | CP0 | 917 | 7/15/1979 | 4.2 | 3.9 | 4.7 |
| Dampierre 1 | CP1 | 937 | 3/15/1980 | 4.5 | 4.0 | 4.9 |
| Dampierre 2 | CP1 | 937 | 12/5/1980 | 4.7 | 4.3 | 5.1 |
| Gravelines 1 | CP1 | 951 | 2/21/1980 | 4.5 | 4.1 | 5.1 |
| Gravelines 2 | CP1 | 951 | 8/2/1980 | 4.7 | 4.2 | 5.1 |
| Gravelines 3 | CP1 | 951 | 11/30/1980 | 4.9 | 4.5 | 5.4 |
| Tricastin 1 | CP1 | 955 | 2/21/1980 | 4.6 | 4.1 | 5.1 |
| Tricastin 2 | CP1 | 955 | 7/22/1980 | 4.6 | 4.2 | 5.1 |
| Blayais 1 | CP1 | 951 | 5/20/1981 | 5.2 | 4.9 | 5.9 |
| Dampierre 3 | CP1 | 937 | 1/25/1981 | 4.8 | 4.4 | 5.2 |
| Dampierre 4 | CP1 | 937 | 8/5/1981 | 5.0 | 4.6 | 5.5 |
| Gravelines 4 | CP1 | 951 | 5/31/1981 | 5.1 | 4.7 | 5.6 |
| Tricastin 3 | CP1 | 955 | 11/29/1980 | 4.8 | 4.3 | 5.2 |
| Tricastin 4 | CP1 | 955 | 5/31/1981 | 4.9 | 4.6 | 5.3 |
| Blayais 2 | CP1 | 951 | 6/28/1982 | 5.5 | 5.2 | 6.5 |
| Blayais 3 | CP1 | 951 | 7/29/1983 | 6.1 | 5.8 | 6.9 |
| Blayais 4 | CP1 | 951 | 5/1/1983 | 6.1 | 5.7 | 6.9 |
| Gravelines 5 | CP1 | 951 | 8/5/1984 | 6.6 | 6.2 | 6.8 |
| Gravelines 6 | CP1 | 951 | 7/21/1985 | 6.7 | 6.3 | 6.8 |
| St Laurent B1 | CP2 | 956 | 1/4/1981 | 5.0 | 4.6 | 6.4 |
| St Laurent B2 | CP2 | 956 | 5/12/1981 | 5.1 | 4.8 | 6.5 |
| Chinon B1 | CP2 | 954 | 10/28/1982 | 5.7 | 5.3 | 6.7 |
| Chinon B2 | CP2 | 954 | 9/23/1983 | 5.9 | 5.5 | 6.6 |
| Cruas 1 | CP2 | 956 | 4/2/1983 | 6.2 | 5.8 | 6.9 |
| Cruas 2 | CP2 | 956 | 8/1/1984 | 6.5 | 6.1 | 6.7 |
| Cruas 3 | CP2 | 956 | 4/9/1984 | 6.5 | 6.2 | 6.8 |
| Cruas 4 | CP2 | 956 | 10/1/1984 | 6.7 | 6.3 | 6.8 |
| Chinon B3 | CP2 | 954 | 9/18/1986 | 7.0 | 6.6 | 7.1 |
| Chinon B4 | CP2 | 954 | 10/13/1987 | 7.3 | 6.9 | 7.6 |
| Paluel 1 | P4 | 1382 | 5/13/1984 | 8.9 | 8.3 | 9.5 |
| Paluel 2 | P4 | 1382 | 8/11/1984 | 9.0 | 8.5 | 9.6 |
| Flamanville 1 | P4 | 1382 | 9/29/1985 | 9.8 | 9.3 | 9.9 |
| Paluel 3 | P4 | 1382 | 8/7/1985 | 9.6 | 9.0 | 9.6 |
| St Alban 1 | P4 | 1381 | 8/4/1985 | 9.5 | 9.0 | 9.6 |
| Flamanville 2 | P4 | 1382 | 6/12/1986 | 10.0 | 9.5 | 10.2 |
| Paluel 4 | P4 | 1382 | 3/29/1986 | 9.9 | 9.3 | 10.0 |
| St Alban 2 | P4 | 1381 | 6/7/1986 | 9.8 | 9.3 | 9.9 |
| Cattenom 1 | P'4 | 1362 | 10/24/1986 | 9.9 | 9.3 | 9.9 |
| Belleville 1 | P'4 | 1363 | 9/9/1987 | 10.2 | 9.8 | 10.5 |
| Cattenom 2 | P'4 | 1362 | 8/7/1987 | 10.2 | 9.7 | 10.5 |
| Nogent 1 | P'4 | 1363 | 9/12/1987 | 10.4 | 9.9 | 11.1 |
| Belleville 2 | P'4 | 1363 | 5/25/1988 | 10.5 | 10.1 | 11.1 |
| Nogent 2 | P'4 | 1363 | 10/4/1988 | 11.1 | 10.7 | 12.4 |
| Cattenom 3 | P'4 | 1362 | 2/16/1990 | 11.9 | 11.7 | 12.7 |
| Golfech 1 | P'4 | 1363 | 4/24/1990 | 12.0 | 11.8 | 12.6 |
| Penly 1 | P'4 | 1382 | 4/1/1990 | 12.1 | 11.9 | 12.8 |
| Cattenom 4 | P'4 | 1362 | 5/4/1991 | 12.7 | 11.7 | 13.0 |
| Penly 2 | P'4 | 1382 | 1/10/1992 | 13.4 | 11.7 | 13.9 |
| Golfech 2 | P'4 | 1363 | 5/21/1993 | 13.3 | 12.5 | 14.2 |
| Chooz B1 | N4 | 1560 | 7/25/1996 | 15.8 | 15.8 | 19.4 |
| Chooz B2 | N4 | 1560 | 3/10/1997 | 16.8 | 16.8 | 18.6 |
| Civaux 1 | N4 | 1561 | 11/29/1997 | 18.7 | 15.9 | 19.8 |
| Civaux 2 | N4 | 1561 | 11/27/1999 | 31.6 | 15.7 | 32.6 |

escalation, or "negative learning"[19] in the terminology of learning/experience curve models. The result may be a much wider cost variation across different technologies than so far anticipated.[20] "Granularity" seems to be key, but the reasons for learning potentials and in the success of their realization need further study.

[19] This is quite different from the examples of "negative learning" discussed in the traditional management literature (e.g. the case of the Lockheed Tristar aircraft referred to by Argote and Epple, 1990) where cost escalations arise from erratic (roller-coaster) production scale-ups leading to organizational "forgetting-by-not-doing" (Rosegger, 1991).

[20] For modeling applications treating learning curve parameters as uncertain, incl. negative learning, see Gritsevskyi and Nakicenovic (2000) and Grubler and Gritsevskyi (2002).

In the meantime, the potential role of nuclear in a climate mitigation technology portfolio cannot be assessed seriously if the lessons from its most successful and intensive deployment, in France, are ignored.

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## Appendix

See Tables A1 and A2.

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