International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

An Assessment of the Costs of the French Nuclear PWR Program 1970-2000

Grubler, A.

IIASA Interim Report
October 2009

International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-09-036

An assessment of the costs of the French nuclear PWR program 1970–2000

Arnulf Grubler (gruebler@iiasa.ac.at)

Approved by

Detlof von Winterfeldt
Director

October 6, 2009

Contents

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, all 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 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 reactor construction costs. Specific costs per kW installed capacity increased by more than a factor of three between the first and last reactor generations built. 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 paper draws a number of cautionary lessons for technology, policy, and modeling studies in a climate-constrained world. First, the inherent technology characteristics of nuclear power: large-scale, complex, and with lumpy investments introduce a significant economic risk of cost overruns in the build-up process. Anticipated economic gains from standardization and ever larger unit scales not only have not materialized, but the corresponding increasing complexity in design and in construction operations have reversed the anticipated learning effects to their contrary: cost escalation. Second, cost projections and policy rationales based on relative economic merits of competing technology options are fraught by persistent uncertainties and biases, suggesting that the real cost of a scale up of a technology as large and complex as nuclear might be in fact unknowable ex ante, severely limiting conventional deterministic economic calculus and decision making (e.g. cost minimization) models. Lastly, 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.

Acknowledgments

Many colleagues have graciously lent their time and expertise in personal interviews, email exchanges, comments, and in providing historical references. I wish to thank in particular: Benjamin Dessus, Dominique Finon, Philippe Girard, Amory Lovins, Yves Marignac, Mycle Schneider, and Steven Thomas for their insights and collegial exchanges. Any errors and misinterpretations of this case study remain entirely with the author. I also wish to thank Jon Koomey and Nate Hultman for making their detailed US data available as well as Peter Kolp for his most useful help in the analysis and preparation of figures.

About the Author

Arnulf Grubler first joined IIASA in 1976 to work with the Energy Systems Program; between 1979 and 1984 he was affiliated with the Resources and Environment Area. He returned to the Institute in 1986 and currently works as a Senior Research Scholar and Acting Leader of the Transitions to New Technologies Program on a part-time basis. He also holds a part-time appointment as Professor in the Field of Energy and Technology at the School of Forestry and Environmental Studies at Yale University, New Haven, USA.

Prof. Grubler received his master's degree in engineering from the Technical University of Vienna, where he was also awarded his Ph.D. He completed his Habilitation (venia legendi in systems science of environment and technology) at the Mining University Leoben, Austria. He is also foreign member elect of the Russian Academy of Natural Sciences.

Arnulf Grubler has been lead and contributing author for the Second, Third, and Forth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, co-recipient of the 2007 Peace Nobel Price). He serves on the editorial boards of *Technological Forecasting and Social Change* and *Journal of Industrial Ecology*.

An assessment of the costs of the French nuclear PWR program 1970–2000

Arnulf Grubler[1]

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 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 historical context and a brief description of the institutional landscape (Sections 2 and 3). (It is beyond the scope of this paper to write a comprehensive social/political history of the French nuclear program as well.)

---

[1] Senior Research Scholar, Transitions to New Technologies (TNT) Program, International institute for Applied Systems Analysis and School of Forestry and Environmental Studies, Yale University.

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 "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 Figure 1. The final resulting technology "map", which remains currently valid, is illustrated in Figure 2. The discussion below draws on the insightful and detailed accounts of 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).

Table 1. Overview of the French PWR program.

Order series	Reactor type	Reactor size GWnet	Number built	Constructed between	Mean construction time months	Sites
CP0	PWR Westinghouse license	900	6	1971-1979	63	Bugey Fessenheim
CP1	As CP0	900	18	1974-1985	65	Blayais Dampierre Gravelines Tricastin
CP2	as CP1	900	10	1976-1987	67	Chinon Cruas St. Laurent
P4	1.3 GW PWR Westinghouse license	1300	8	1977-1986	78	Flamaville Paluel St. Alban
P’4	P4 “frenchified” Westinghouse	1300	12	1979-1993	90	Belleville Cattenom Golfech Nogent Penly
N4	PWR new French design	1500	4	1984-1999	126	Chooz Civeaux
EPR	EPR Framatome-Siemens	1600	1	2007-		Flamanville

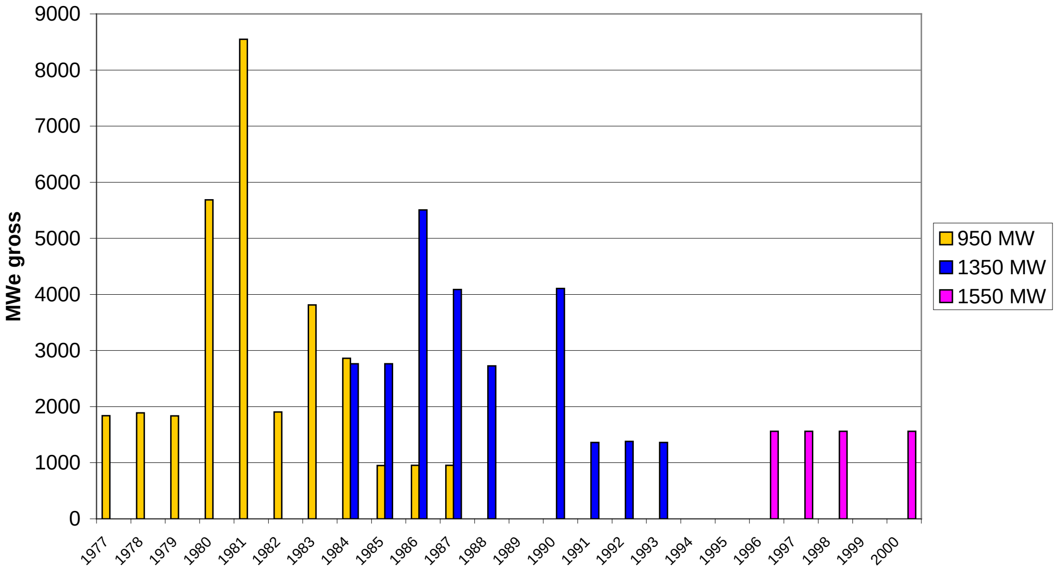

Figure 1. Rhythm of the French nuclear PWR program (grid connections of MWgross by major type). Source: IAEA PRIS data base (2009).

Figure 2. Map of French nuclear installations. Source: Marignac et al., 2008:36.

de Gaulle (1959–1969)

In this first period (for a concise account see e.g. Bupp and Derian, 1978, and Thomas, 1988) a strong domestic nuclear knowledge base was developed at a cost of cumulative R&D expenditures of more than 100 billion French Francs in constant 1998 money, or some 20 billion US$ 2008—plus a substantial but unknown amount of military nuclear-related expenditures.

Technology development and investments were initially dominated by military applications (submarine reactors, and reactors and reprocessing for military plutonium production) with civilian "spin-offs" in form of natural uranium graphite-gas-reactors spearheaded by the *Commissariat pour l'Énergie Atomique* (the CEA) and somewhat cautiously adopted by the French national utility *Électricité de France* (ÉDF). Research and demonstration reactors based on Heavy Water, Pressurized Water, and also Fast Breeder designs were also built. The installed "commercial" nuclear capacity, not counting experimental or small-scale reactors by 1969 however totaled only 3 units or 1.2 GWe: all graphite gas reactors.

Pompidou (1969–1974)

The long-standing "battle of reactor designs" between ÉDF and the CEA was finally resolved[2] in 1970 by abandoning the domestic graphite-gas reactor design advocated by the CEA, in favor of larger, US licensed Westinghouse reactors as ÉDF envisaged. This shift was made possible by the erosion of the anti-American stance of the de Gaulle era. (The only light water reactor successor technology to be actively pursued in France under this vision was the fast breeder reactor (FBR), with the 0.25 GW Phénix unit completed in 1973 and the 1.2 GW Super-Phénix ordered in the same year.) The “reactor battle” was fought out and resolved within a commission that coordinated the various nuclear stakeholders: the *Commission Consultative pour la Production d'Électricité d'Origine Nucléaire* (PEON), which subsequently proved instrumental in developing a "technology road map" for scaling-up of nuclear electricity generation[3] and in communicating the anticipated economic advantages within the French energy technocratic elites.[4]

The ÉDF policy of maintaining competition between equipment suppliers led to the initial ordering of both pressurized water reactors (6 PWRs under Westinghouse license) and boiling water reactors (2 BWRs under General Electric license) from an initially fragmented nuclear equipment supply industry, This second "battle of reactor designs and industries" (for an insider’s account, see Boiteux, 2009) was resolved by

---

[2] Given the fierce battling over the issue of reactor design choice, this "truce" between ÉDF and the CEA might legitimately be referred to as a "nuclear Yalta". As it turned out, the decision to standardize on well tested US PWRs was the most influential for the subsequent success of the program (and in abandoning this success model, economic disappointment was quasi inevitable).

[3] Initial ÉDF projections anticipated 1000 TWh electricity consumption by 2000 to be supplied by 80 PWRs and 20 FBRs (hence the perceived urgency to develop a large-scale commercial Fast Breeder Reactor FBR). The PEON Commission report in 1973 projected France’s electricity demand as 400 TWh in 1985 and 750 TWh in 2000, compared to actual numbers of 300 and 430 TWh respectively (G-M-T, 2000:373). These over-projections of demand growth led subsequently to substantial (and costly) overcapacity in orders and construction, requiring not un-painful adjustments.

[4] A central instrument of this communication was the regularly updated *Coûts de Référence* (reference electricity cost) projections. See also Section 5 below.

1975/1976, standardizing exclusively on the Westinghouse PWR design. Scaling-up was then comparatively easy technologically, using proven Westinghouse-licensed designs— using initially the US Beaver Valley and later the North Anna plant as reference.

Even before the oil crisis, the path towards a massive upscaling of French PWRs and related industries was a shared consensus among France’s energy technocratic elite. When the oil crisis hit in 1973, this technocratic vision was elevated to a top national political priority. Prime Minister Pierre Messmer announced an ambitious plan (*le plan Messmer*) to order some 13 GW of reactors within two years. This pattern of centralized, government-supported contract orders of large numbers of reactors has characterized the entirety of the French nuclear PWR scale-up as well as the design modifications introduced only at each successive new “bulk” order. While the total installed nuclear capacity for all types of reactors, including experimental ones, was still comparatively modest at some 3 GW by 1974, 6 PWR units were ordered in 1970–1973 and another 6 units in 1974, all of the original Westinghouse-licensed 900 MW type.

The last "missing link" in preparing for the subsequent scale-up was to develop a strong domestic components manufacturing industry, which unlike those of the US or Germany had remained fragmented and relatively weak, as well as the domestic capability to manage the entire PWR fuel cycle. In a complex series of mergers and restructurings, *Framatome* emerged as the main actor for nuclear components (and swiftly opened two large manufacturing plants by 1975); *Alsthom*, for turbines and generators; and in 1976, COGEMA for the entire fuel cycle, including the *Eurodif* enrichment facility (which ultimately would consume the entire electricity output of 3 Tricastin reactors) 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. The stage was set for the subsequent nuclear *belle époque*.

Giscard (1974–1981)

This period is overshadowed by the unfolding of the consequences of the two "oil shocks" that reinforced the political legitimacy[5] of the ambitious nuclear investment program. The oil shocks also paved the way for the subsequent nuclear overcapacity, as slackening demand growth remained unreflected in the bullish demand and capacity expansion projections and orders. Thus the French PWR program remained at full throttle regardless of external circumstances. Orders of 5–6 reactors per year, supplemented by grid-connections of the first reactors commissioned in the previous period, and first operating experiences from initial reactors became available in the late 1970s.

Four developments are particularly noteworthy in this period.

[5] Public opposition somehow grew in the 1975–1977 period (at the political level supported by the Socialist Party and its associated Trade Unions) but subsided after some demonstrations turned violent and it became apparent that nothing would effectively influence the “etatist” nuclear policy. (See Bupp and Derian, 1978, and Thomas, 1988 for more details.)

First was a transition to a larger PWR reactor design, the 1.3 GW PWR, again under Westinghouse license and modeled after a US reactor (South Texas). The reason for this increase in reactor unit scale was primarily economic: significant economies of scale were sought and expected to encounter increasing tendencies for cost escalation.

Second, in a series of delicate negotiations aimed to resolve the tension between the economic realism of ÉDF and the manufacturing industry on one hand, and the technology "push" perspective of the CEA on the other, a decision was reached to "frenchify" the reactor components as much as possible, with the long-term objective to become altogether independent of the Westinghouse license[6] (Finon and Staropoli, 2001:187).

Third, with the completion of the first reactors, the earlier optimistic assumptions about construction duration and investment costs faced a harsh reality check. The first reactor completed, at Fessenheim, took two years longer to build than originally projected, accruing additional interest during construction that further added to other cost escalation factors. As more experience was accumulated, the cost projections of the PEON Commission, as well as the internal ones of ÉDF, started to rise as well, adding urgency to the economic rationale for the move to the 1.3 GW PWR design. One French reference (though discussions of cost are extremely rare in this period) put the escalation of real investment per kW at 50% or 4.4%/year during 1974–1984 (as reported by Crowley and Kaminski, 1985). Yet these trends did not cause alarm, as other countries were suffering even worse escalation—as in Germany and especially the US, with 10–15% real cost escalation per year. And there was always the option of moving to much larger units.[7] But as it turned out later, the expectations of significant economies of scale proved unfounded: any cost reductions from larger components were more than offset by more complex construction sites, longer construction times, and the need to fix the inevitable technical problems arising from significant design changes.

Lastly, with a massive construction program well underway, it became clear that orders needed substantial reduction, as already the program *en cours* would result in significant overcapacity. Added to this were concerns about the rapidly rising debt of ÉDF, which passed the psychological threshold of 100 billion nominal French Francs in 1980/1981 (Bataille and Galley, 1999), continuing to some 230 billion nominal FF by the end of the 1980s (Nectoux, 1991:84).[8]

---

[6] CEA's ultimate triumph was anticipated to be the entirely French N4 reactor. 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, 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).

[7] One of the authors of the G-M-T report, Philippe Girard (email correspondence with the author, 21 July 2009) draws an analogy to the aircraft industry: the almost obsessive focus on ever larger reactors, culminating in the 1.6 GW EPR design, is as if the aircraft industry focused exclusively on wide-body aircraft like the Boeing 747 or the Airbus A380, significantly limiting market potentials.

[8] In the early1980s, EDF's debt represented close to 200 percent of its entire annual turnover (Nectoux, 1991:84).

Finally, on the political level a window of opportunity for nuclear discontent seemed to open in the presidential elections when the candidate of the Socialist Party, François Mitterrand, advanced a reevaluation of the nuclear program in general (with a temporary halt to new orders pending a national debate and a referendum) and of the fast breeder reactor in particular.

Mitterrand (1981–1995)

Despite the rhetoric during the election campaign, things remained essentially "business as usual".[9] The national debate shrank to a two-day parliamentary debate, resulting "in a policy which differed little from that which would have been followed by the previous government" (Thomas, 1988:213). Reprocessing and the fast breeder continued.[10] The oversized reactor order program was reduced in 1982/1983 from 9 to 6 units. An internal review basically concluded that no new orders were needed to meet electricity demand but some would be desirable for maintaining an industrial and competence base. The formerly ambitious scale-up program was then downsized to some two orders per year. After 1986, only two N4 reactors were ordered, completing the nuclear expansion program in France.

Despite stopping further orders and drastically reducing the construction program, the built-up nuclear overcapacity was to persist, requiring large-scale electricity exports (typically some 77 TWh/yr net, or 20% of nuclear electricity generated) as well as stimulating domestic electricity demand growth (particularly for thermal uses, notably electric resistance heating, which was adopted in two-thirds of new French dwellings: Thomas, 1988:217).[11] More significantly, faced with the challenge of how to reconcile the baseload characteristic of nuclear power (but with a share of 80% in total electricity generation) with the vagaries of the electricity demand load curve,

---

[9] International concerns about losing the nuclear industry's showcase --and hopes of losing one major competitor-- were quickly dispelled. Ferrari (1984) describes the new government's energy and nuclear policy as "less spectacular but [carrying] more learning". (Ferrari's key role within the French nuclear nexus can perhaps be best inferred from his having been invited to comment on the Charpin-Dessus-Pellat report upon its publication, well after his active career in the industry had ended [Ferrari, 2000].)

[10] Huge technical problems soon became apparent at the Superphénix fast breeder reactor: In 1987 a major sodium leak was discovered in the fuel transfer tank. Due to a design mistake, the tank could not be repaired and it took ten months to develop a new technique to load/unload the fuel from the reactor core, moving the primary coolant sodium into a new transfer tank. A lengthy public enquiry and hearings followed until a new operating license was finally issued in 1994. The reactor was restarted in 1996, and finally shut down for good at the end of the same year. In 1997, Prime Minister Jospin announced the abandonment of Superphénix, putting to rest the French technological vision of the fast breeder reactor as LWRs' "inevitable" successor. All other fast breeder reactor projects (Superphénix2, and the FBR and integrated fuel cycle complex of St. Etienne des Sorts) were also cancelled.

[11] This emphasis on supply-side energy policies, especially nuclear power, to the detriment of energy efficiency programs resulted in deflating another myth of the French nuclear program: its presumed lessening of oil import dependence. Compared to neighbor Italy, which operates no nuclear plants (but eagerly imports French nuclear electricity), French per-capita oil use is actually higher: 1.5 toe/capita in 2007, *vs.* 1.3 for Italy, or for the average of all EU-27 countries (see Schneider's (2009c) rebuttal to the very optimistic assessment of the success of the French program by Kidd (2009)). The most significant and duly noted finding from the C-D-P (2000) report's scenarios was that a scenario of enhanced efficiency and conservation efforts would actually turn out to be cheaper than a continuation of "business as usual" supply-side dominated policies and subsequent replacement of the existing, ageing nuclear reactor fleet. However, this alternative policy has not yet been debated (not to mention adopted) in France.

ÉDF rose to the occasion and developed a system of "load modulation" of its reactors via additional "grey" control rods.

The resulting lower load factor—roughly 80%, substantially less in some years, compared to the roughly 90% of typical baseload reactor operation[12]) implied an economic penalty, apparently accepted in return for the system's running smoothly and reliably. Nonetheless, over the subsequent years an inherent tension developed between the (to a large extent unsuccessful) efforts to stimulate electricity consumption and the baseload characteristics of nuclear power. The gap between minima and maxima of daily loads rose from some 27 GW in 1978 to some 45 GW in the mid-1990s, then to 57 GW by 2006 (Schneider 2008:23) and 61 GW by February 2009 (Schneider, *pers. comm.),* implying that most of the reactors needed to be operated in load modulation mode.

The *de facto* moratorium on further orders for the domestic market, and a lack of export markets, posed a serious challenge to the French equipment manufacturing industry. For reasons largely unrelated to the nuclear business, Creusot-Loire, a major shareholder of Framatome, went bankrupt in 1984, leaving the CEA as sole shareholder and necessitating a major restructuring of Framatome's ownership in 1985 (Thomas, 1988:217). The few remaining construction orders also had to be spread out over more years to maintain both jobs and the knowledge base. The effects of this "spreading" on lengthened construction times and on cost escalation, particularly on the later 1300 MW P'4 and the N4 units, remain debated among scholars, but the phenomenon appears plausible and was corroborated by ÉDF insiders (Boiteux, 2009).

Chirac (1995–2007)

This period may be best characterized as one of stagnation and of the sunset of earlier hopes of vibrant expansion for the nuclear "enterprise", as well as for the French "étatist" system in terms of directed technology policy—perhaps even for the entire political system, which appeared increasingly "fossilized" in the Chirac era. With the previous nuclear expansions completed, construction of the last remaining N4 reactors was "stretched out", and doubts started to creep in. First was the disappointing experience on the construction sites of the four N4 reactors—especially the two Chooz units that took 12 years between construction start and first criticality, plus another 3-4 years until commercial operation (IAEA, PRIS, 2009). Design flaws also took sudden center-stage in the media (e.g., MacLachlan, 1991). A design flaw co-located hot and cold pipes in the primary circuit, leading to enormous thermal stresses and a spectacular leak in 1998 and thus requiring redesign. Digitizing the control system also turned out to be a veritable N4 nightmare, among other problems.

[12] French lifetime reactor load factors are (independent of which indicator is chosen) actually quite close to the world average (IAEA PRIS, 2009). The difference between French nuclear load modulation and classical nuclear base-load operation can best be discerned by comparing France to its neighbor Switzerland: a lifetime operating factor of 77% (France) to 86.5% in Switzerland (IAEA PRIS, 2009).

The French nuclear industry needed to consolidate whilst maintaining its ambition for technological innovation, in particular to develop a successor to the N4 reactor—the European Pressurized Water Reactor, EPR.

In 2001, Framatome and COGEMA (now AREVA NC) merged to form AREVA, which was essentially owned by the CEA, i.e., the French government. Also, AREVA uncharacteristically entered a joint venture with Siemens of Germany in the development of the EPR, and Framatome ANP was founded with a minority Siemens stake, renamed AREVA NP in 2006.[13] Construction of the first EPR in France started in December 2007 at the Flamanville site of two N4 reactors, along an entirely classical scenario, i.e., with over-optimistic projections of construction duration and cost. (The delays and likely substantial cost overruns of Flamanville-3 are watched very carefully by both proponents and opponents of a nuclear "renaissance", mostly because of its high symbolic value.[14]

Additional signs of erosion of the shared consensus about the economic advantages of nuclear power emerged. In 1997, the reference cost projections (DIGEC, 1997) published by the Ministry of Industry and superseding the PEON projections, for the first time included a scenario in which natural-gas combined- cycle plants could be as cheap[15] as nuclear for baseload generation. This seemingly innocuous event was the first time nuclear failed to be reported as the cheapest option since the 1960s: it had always won under all assumptions. Another sign of the erosion of the traditional nuclear French "consensus" was the governmental request for an in-depth evaluation of the economics of the nuclear option. This led in 2000 to the publication of the Charpin, Dessus, Pellat (C-D-P) report, whose technical appendices revealed for the first time the actual expenditures and costs of the French nuclear program (see Section 4 below).

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), and finally "*mortals*" (the general public). The institutional key to success in France was the extremely limited number of institutional actors: "mortals" never

---

[13] In 2009, Siemens announced its intention to end its partnership Areva NP, selling its 34% share back to AREVA. Under the contractual terms AREVA is obliged to buy back the Siemens shares latest by 2012.

[14] When the first EPR, the AREVA/Siemens Olkiluoto-3 project, went at least three years behind schedule and 50% over budget, AREVA could and did blame this on its foreign partners, but no such explanation was plausible for the identical Flamanville-3 EPR built by and for French institutions in France. When after a year's construction the project was a year late and 20% over budget, doubts arose about whether AREVA's last order before Olkiluoto-3, in 1992, was so long ago that critical design and construction skills may have atrophied.

[15] This result was even more noticeable when considering the study's assumptions. Compared to USDOE projections available at the time, nuclear was assumed to be some 30% cheaper, but gas some 20% more expensive in France compared to the US (Boisson, 1998:143).

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 departments). 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 technology program.

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 electromechanical manufacturing industry* [emerging in the scaleup 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[16]) 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, e.g., the successive reports of the PEON Commission.

The role of coordination fell on a small technocratic elite of state engineers, the so-called *Corps d'État'*[17], whose members continue to be strongly represented within the Ministry of Industry, ÉDF, the CEA, and the nuclear equipment industry. The

---

[16] 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).

[17] 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 (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).

institutional locus of this elite technocracy was the PEON (1969–1981) Commission, 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 Figure 3 and Table 1 above). While a certain increase across the various reactor generations built is evident form the data[18] (IEA 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.

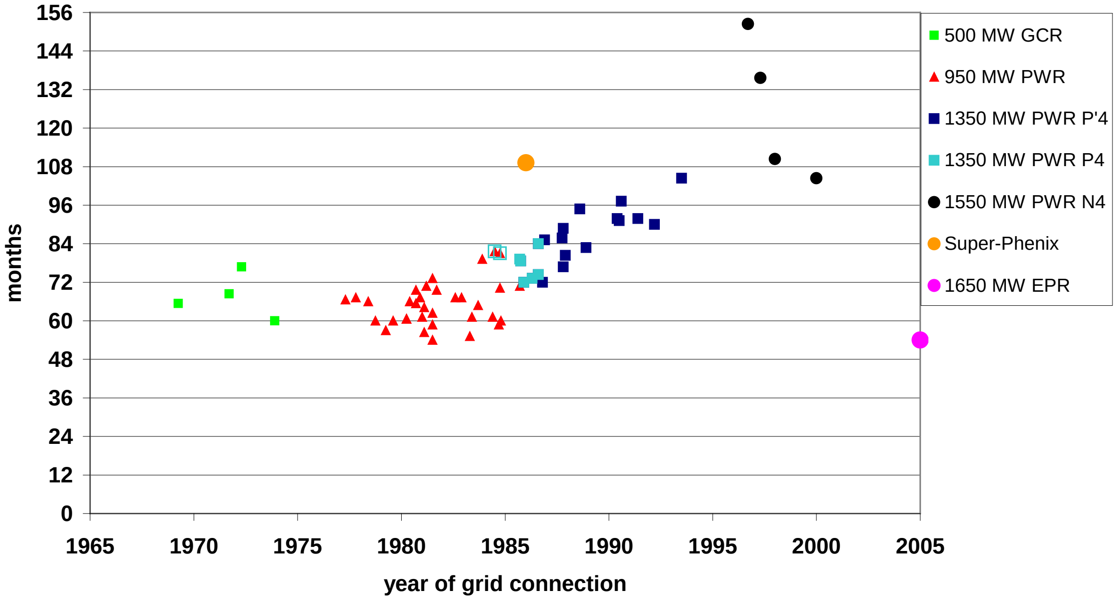

Figure 3. Construction time of French reactors (construction start to first grid-connection, in months). Note in particular the entirely implausible, optimistic projection for the new 1650 MW EPR reactor Flamanville-3 submitted by the French authorities to the IAEA. Source: IAEA PRIS Data Base (2009).

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[19]. 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"). Standardization, however, requires continued, dedicated

[18] Measuring months from construction start to first grid connection.
[19] This nationalized, powerful utility has often been referred to as "state within the state" by critics (e.g. Gravelaine and O'Dy, 1978)

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*."[20] 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 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, 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.

---

[20] 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.)

The only economic information widely used within France's nuclear nexus was cost *projections*—in particular, the regularly updated "reference cost" projections by the PEON Commission[21] (succeeded after 1981 by the reference cost projections elaborated by the DIGEC of the Ministry of Industry[22]). Yet these were *de facto* unavailable to "outsiders", including French academics. 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 Philippe Girard, Yves Marignac, and Jean Tassart (G-M-T, 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

[21] It is interesting to note that prior to 2000, the PEON Commission's reference costs projections, whilst in principle in the public domain, seemed to have been a well-kept secret, as no reference to them can be found in the literature. 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 projections 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.
[22] DIGEC: Direction du Gaz, de l'Électricité et du Charbon, Direction Générale de l'Énergie et des Matières Premières of the Ministry of Industry. 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.

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 to 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[23] 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.**[24] 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 below. 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[25] estimate the upper bound of Table 2, the costs of the French PWR program translate into 230 billion Euros(2008) or 330 billion US$2008.

[23] Introduced as legal tender on January 1st 2002.
[24] For a speculative and overly simplistic update, cf. footnote 31 below.
[25] 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 star are from G-G, 1999.

R&D < 1970		104	
R&D public > 1970	57	57	
Investments			
PWR construction			
PWRs	460*	480	
End-of-fuel cycle and decommissioning provision	169	169	
Subtotal capital	**686**	**810**	
Operation expenditures			
O&M	400*	402	
Fuel	419*	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

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[26] 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 to 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 to 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

[26] 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.

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 Figures 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/y). Evidently, as the program was completed, the structure of these expenditures shifted from investment to operating expenditures.

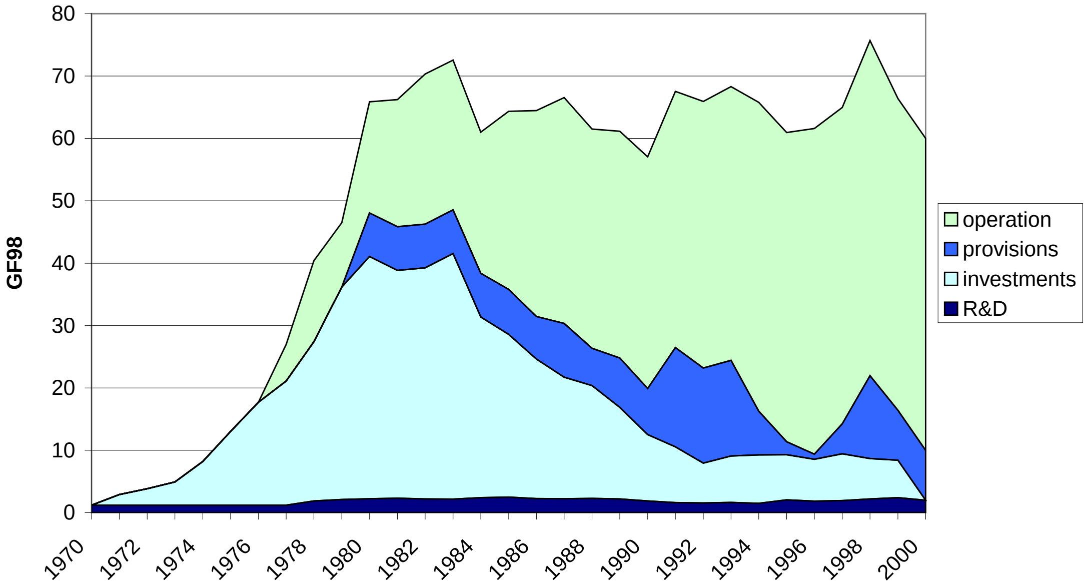

Figure 4. Expenditures per year for French PWR program 1970-2000 in Billion French Francs1998 (GFF98), by major expenditure type. Source G-M-T, 2000.

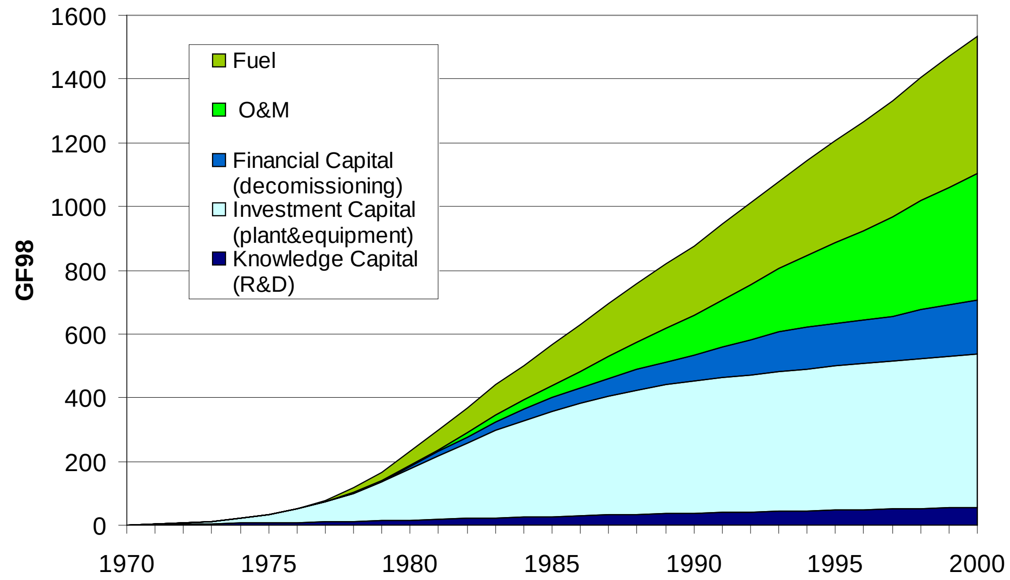

Figure 5. Cumulative expenditure of the French PWR program 1970–2000 in Billion French Francs1998 (GFF98, conservative range of estimates available). See also Table 2.

Using a real annual discount rate of 5 percent[27], 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.

That averaging over the entire 26-year program, however, masks decisive differences in the economics 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 allow us to identify investments costs per individual reactor or per specific reactor generation, one nonetheless can infer from the annual construction expenditure (see Figure 4) some general trends over time based on some simple, plausible arithmetic.

Estimation Method:

The method is simple: Construction investments are constrained by construction duration, over which expenditures follow typically a triangular distribution.

---

[27] Levelized costs vary between 0.2 and 0.24 FF98/kWh when deploying a real annual discount rate of 10 and 3 percent respectively.

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 Figure 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 constructed in a particular year, yielding the average specific construction costs per kW over time. We perform this calculation for two data sets of construction expenditures based on the data given in Girard, Marignac, and Tassart (G-M-T, 2000: 125) and by Bataille and Galley (1999: Tableau Investissements d'ÉDF[28]). These data sources are summarized in Figure 7. Altogether 24 scenarios of annual costs per kW have been calculated for the "best guess" cost estimates as well as the two uncertainty ranges ("uncertainty-1", min/max of all scenarios).

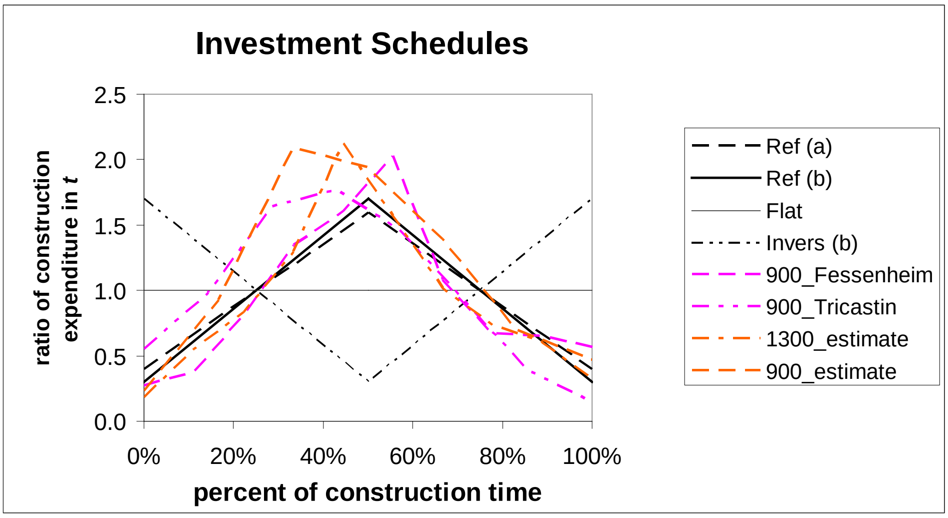

Figure 6. Four illustrative profiles (black) of construction expenditures over time (percent of total elapsed construction time) used in modeling specific construction costs, compared to actual construction expenditure profiles (magenta) of the Fessenheim and Tricastin 900 MW reactors (PEON, 1979) and 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. Figure 7). For further explanation see text.

[28] Current FF have been converted to constant FF of 1998 using the French GDP deflator. Incomplete data have been estimated based on the difference to the cumulative grand total of 480 GF98 reported in G-M-T 2000:125 (and are denoted by open symbols in Figure 7).

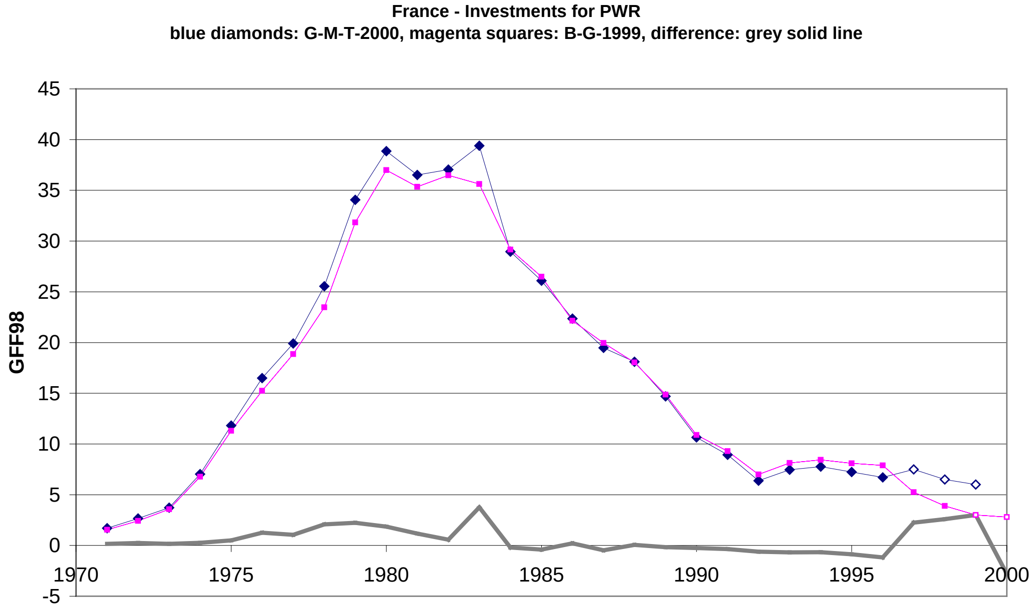

Figure 7. Comparison of two reported PWR construction expenditures (F-M-T, 2000 *vs* B-G, 1999) and their difference in GFF98. Open symbols indicate extrapolations for incomplete reporting derived from the program grand totals of 480 GF98 from G-M-T 2000:125.

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				
	Criticality		x	x
	Grid-connection	x	x	x
	Comm. operation			x
Expenditure profile				
	Reference model	x	x	x
	Model-c (triangular)			x
	Model-a (constant)			x
	Model-b (inverse)			x

Results:

The results are summarized in Figure 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 Figure 8 implies the combination of quite implausible assumptions[29], so it is reported here only for completeness.

[29] E.g. end of construction expenditures with first criticality date (reached for 3 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.

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 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 Figure 8, respectively pegged somewhat arbitrarily to the years 1972 and 1995. These two constructed points refer to the average costs of the first CP0[30] reactors and of the last N4 reactors.

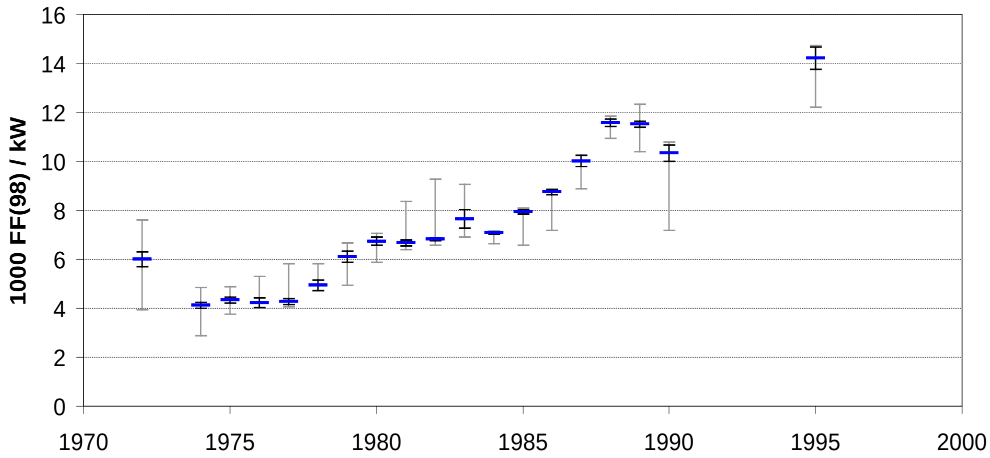

Figure 8. Specific investment costs of French PWRs (100 FF98 per kW) over time, best guess model (blue) estimates and 2 uncertainty ranges (black and grey). The largest uncertainty range refers to minima and maxima of all cost estimation scenarios calculated respectively, which not necessarily combine 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.

Despite some shortcomings of the analysis that are unavoidable until reactor-specific investment cost data become available, 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 4,200 to 7,000 FF98/kW (gross capacity), or by some 5% per annum. Between 1984 and 1990, costs escalated from some 7,000 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).

This observed real cost escalation is quite robust against the data and model uncertainties that can be explored. The reference model suggest a cost escalation from 4,200-4,400 to 14,500 FF98 between the CP0/CP1 reactors constructed during 1974–

[30] 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 Figure 8 assume therefore that expenditures started in fact one year before the officially reported construction start for the CP0 series. The larger uncertainty range results relax this plausible assumption.

1977 and the last N4 reactors constructed in the mid-1990s, i.e., by a factor of 3.4. The respective ratio on the upper and lower bounds of the "reasonable" uncertainty-1 range (4,000-4,200 FF98/kW in 1974) *vs*. 13,800-14,700 FF98/kW[31] for the N4 reactors also yields an increase by a factor of 3.5. Taking the min/max values of all scenarios calculated, the costs escalated from a full range of model estimates of 2,900-4,800 FF98/kW in 1974 to 12,200-14,700 FF98/kW for the N4 reactors—a ratio of between 3 (max scenario values) and 4.2 (min scenario values). We conclude, therefore, that the **last N4 PWR reactors built were some 3.5 times more expensive, in constant Francs per kW, than the early 900-MW units** that started the French PWR program.

Figure 9 shows the same cost escalation as reported in Figure 8 above but in the metric of a learning/experience curve (i.e., costs versus cumulative installed capacity) illustrating the specifics of the French PWR case. (Corresponding cautionary remarks on the pitfalls and limitations of cost projections via aggregate trend curves are given in the Concluding Section 6.)

[31] Using the N4 costs as a precursor model of the subsequent EPR design, one might speculate on updating its costs to current conditions. Converting the N4 14,700 FF98/kW into 2007 money and considering a cost escalation factor of 1.5 based on the Handy-Whitman (Whitman, Requardt & Assocs., 2008) construction cost index (which has well reflected French cost escalation well over the period 1975–1990) yields a conservative estimate of at least 3,000 Euro (2007) or 4,500 US$2007 per kW under current conditions for a N4/EPR design reactor under favorable (French) construction conditions. This lower-bound estimate is still higher than the recent MIT update (Deutch *et al.*, 2009) of nuclear construction costs of some 4,000 US$/kW, suggesting that the MIT estimates are once again optimistic. Only the future, and an unexpected shift to cost transparency, will reveal how the two EPRs under construction in Finland and France will compare to this speculative exercise. In the meantime, climate policy analysts may well be advised to consider nuclear construction costs to the tune of 5,000 US$/kW (i.e. a number close to solar PVs) in scenarios and sensitivity analyses. Even this may prove conservative, since some utility and financial-analyst estimates of nuclear construction cost published in the US in 2008 approach 8000$/kW (US$ 2007 including interest during construction, for a summary see Schlissel and Biewald, 2008).

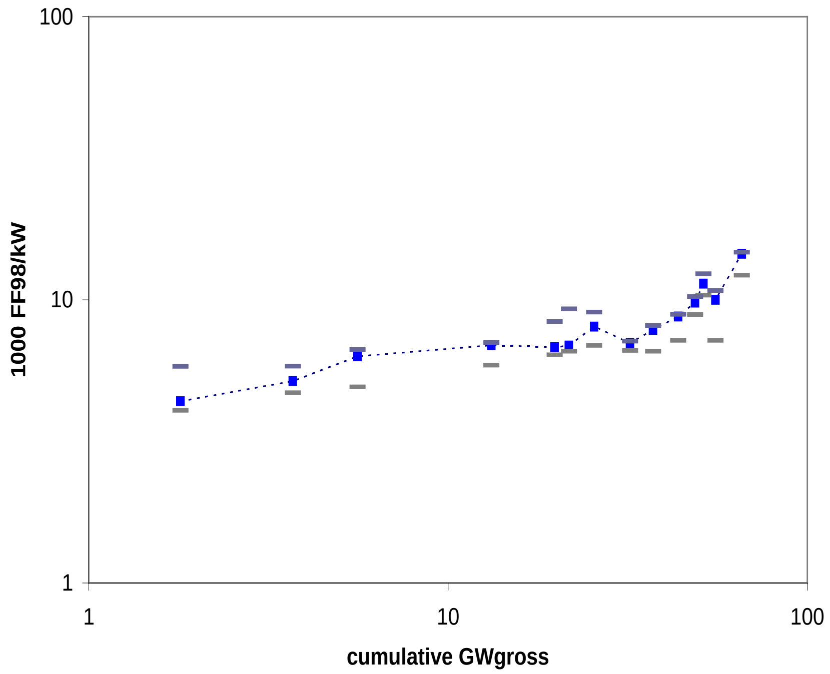

Figure 9. Learning curve of PWR construction costs (1000 FF98/kW, from Figure 8) versus cumulative GWgross connected to grid since 1977. Note the trend break at 30 GW that occurred in 1983, with a significantly accelerated cost escalation thereafter, suggesting the limits of simple learning curve approaches for capturing the dynamics of complex, large-scale technologies.

This cost escalation is far above what would be expected just from longer construction times. The reasons for this cost escalation await further detailed research, but 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 overcapacity); and above all, the unsuccessful attempt to introduce a radically new, entirely French design towards the end of the program that did not allow any learning spillovers in design or construction.

The reactor design changes undeniably improved safety features (Thomas, 1988, and Bataille and Birreaux, 2003, who compares 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. 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 Figure 10, but not as a time trend but instead against cumulative electricity generation for the period 1979 to 1998 (in analogy to Figure 9 above).

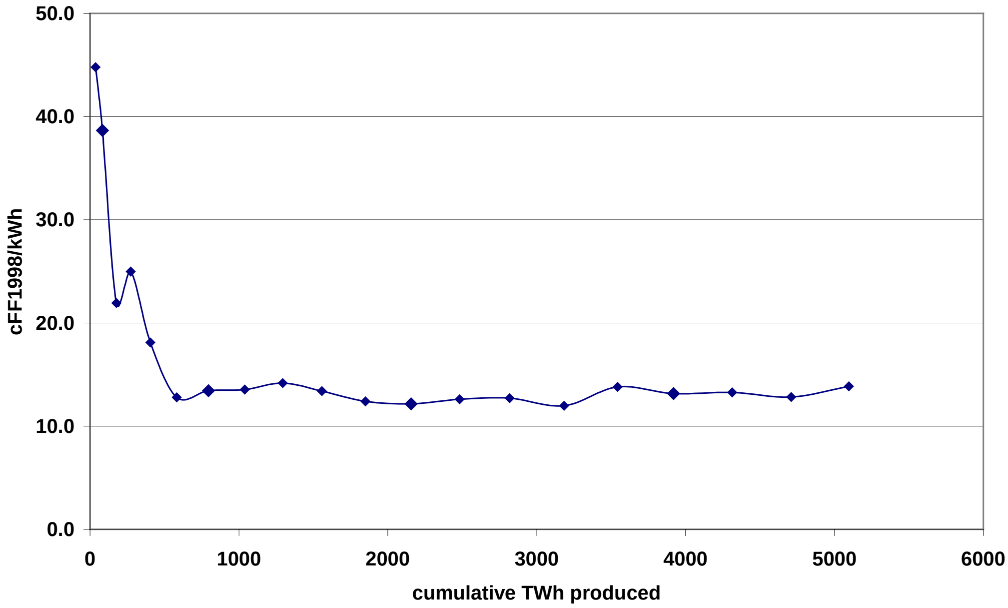

Figure 10. Average operating costs (in centimes FF98 per kWh) of French PWR fleet 1979 to 1998 versus cumulative TWh electricity generated.

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.

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 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.[32]

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 (Figure 11).

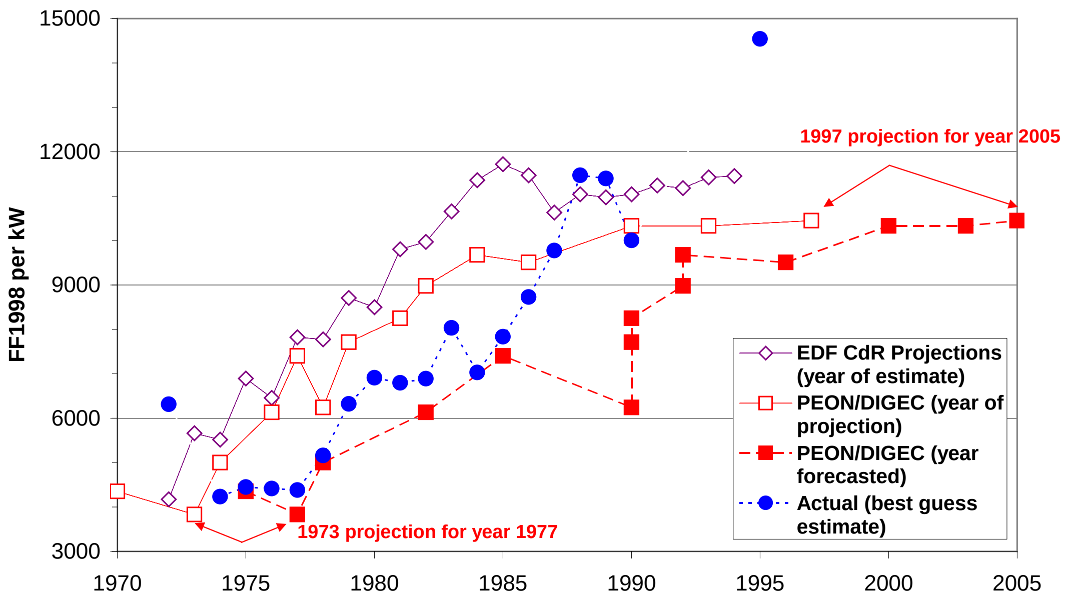

Figure 11. Cost projections (FF98 per kW installed) by ÉDF and PEON/DIGEC versus estimated actual costs (best guess model).

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

[32] 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.

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)[33] 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.[34]

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,

[33] For instance, EDFs CdR projection made in 1976 projected nuclear investment costs for the year 1985 below 6,500 FF98/kW, but two years later, the 1978 CdR, again projecting for 1985, foresaw some 7,800 FF98/kW, in good agreement to our "best guess" *ex post* estimate of average construction costs in 1985—7,833 FF98/kW.

[34] In an almost farcical endpoint in decline of forecasting culture, the latest reference cost projections (DGEC, 2008) do not even contain any concrete cost numbers, comparing options instead through relative indices with nuclear set as 100.

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. Specific investment costs increased by at least a factor of three. While this increase is substantially lower than in other countries (most notably the US, see Figure 12[35]), it nonetheless raises a number of fundamental issues worth considering in a climate-constrained world.

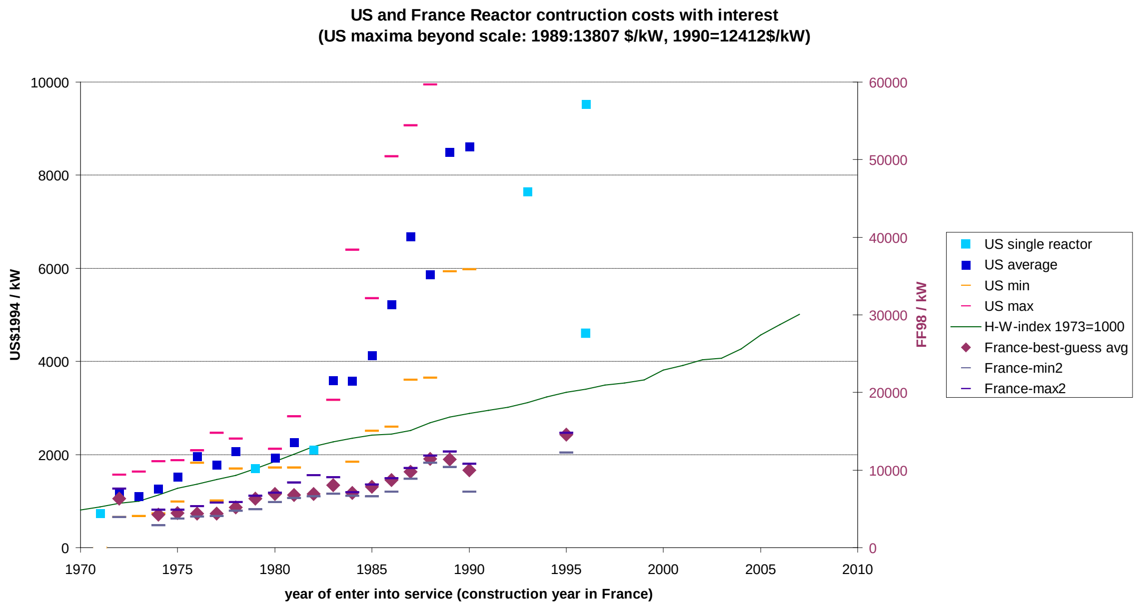

Figure 12. Comparison of French (FF98/kW, this study) and US (US$94/kW, Koomey and Hultman, 2007) nuclear construction costs with Handy-Whitman US nuclear construction cost index (1973=1000). The different metrics are scaled in proportion to the 1998 US$-FF exchange rate. During 1975–1990, French nuclear construction costs followed quite closely the dynamics of cost escalation as estimated by the H-W index; the last built N4 reactors (average plotted at year 1995) are some 35% above the cost escalation suggested by the H-W index.

[35] Given the almost identical technological characteristics of reactors in the US compared to France, Figure 12 powerfully illustrates the impacts on the economics of scaling-up large-scale, complex technologies resulting from different institutional settings. 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 US system.

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 the corresponding 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 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. 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.[36]

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 three times the original estimate. Nuclear is not the only example of a large-scale, other complex technology that might be subject to this engineering rule as well: coal-based integrated gasification combined cycles with carbon capture and sequestration (or very large-scale solar plants in desert areas) would be prime candidates.

Lastly, the French nuclear case has also demonstrated the limits of the learning paradigm: the assumption that costs invariably decrease with accumulated technology

[36] 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.

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 Figure 9 above.

In symmetry to the often evoked "learning-by-doing" phenomenon, there appears not only to be "forgetting by not doing" (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 fundamental characteristics 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 escalation, or "negative learning"[37] in the terminology of learning/experience curve models.

The result may be a much wider variation across different technologies than so far anticipated.[38] "Granularity" seems to be key, but the reasons for learning potentials and in the success of their realization need further study.

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.

7 References

Argote L., and Epple, D., 1990. Learning curves in manufacturing." *Science* **247**(4945): 920-924.

Bataille, M.M., and Birraux, C., 2003. La Durée de Vie des Centrales Nucléaires et les Nouveaux Types de Réacteurs. Office Parlementaire d'Évaluation des Choix Scientifiques et Technologiques. Assemblée Nationale No. 832. Paris. http://www.assemblee-nationale.fr/12/rap-off/i0832.asp

Bataille, C., and Galley, R. (B-G), 1999. Rapport sur l'Aval du Cycle Nucléaire, Tome II : Les Coûts de Production de l'Électricité, Office Parlementaire

[37] 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).

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

d'Évaluation des Choix Scientifiques et Technologiques, Assemblée Nationale, Doc. No. 1359, Paris. http://www.assemblee-nationale.fr/11/rap-off/i1359.asp

Bergeron, J., Schapira, J-P., and Simon, A.,2000. La Prospective Technologique de la Filière Nucléaire : Rapport. La Documentation Française, Paris. http://www.ladocumentationfrancaise.fr/rapports-publics/014000119/index.shtml

Boiteux, M., 2009. Le Programme Électro-Nucléaire : ÉDF et ses Choix Industriels (testimony May 11, 2004). In*: État et Énergie: XIX*^{e}*–XX*^{e} *Siècle*, Comité pour l'Histoire Économique et Financière de la France, Ministère de l'Économie de l'Industrie et de l'Emplois, Paris, pp. 407–418.

Boisson P., 1998. Énergie 2010–2020, Les Chemins d'une Croissance Sobre. La Documentation Française, Paris.

Bupp, I.C., and Derian J-C., 1978. Light Water: how the Nuclear Dream Dissolved. Basic books, New York.

Cantor, R., and Hewlett, J., 1988. The Economics of Nuclear Power: Further Evidence on Learning, Economies of Scale and Regulatory Effects. *Resources and Energy* 10:315–335.

Charpin J-M., Dessus, B., and Pellat, R. (C-D-P), 2000. Étude Économique Prospective de la Filière Électrique Nucléaire, Rapport au Premier Ministre, La Documentation Française, Paris. http://www.ladocumentationfrancaise.fr/rapports-publics/004001472/index.shtml

Cohn, S.M., 1997. Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream. State University of New York Press, Albany.

Crowley, J.H., and Kaminski, R.S., 1985. What the USA can learn from France about keeping costs under control. *Nuclear Engineering International* (July 1985):34–36.

Damian, M., 1992. Nuclear Power: The Ambiguous Lessons of History. *Energy Policy* 20(7):596–607.

Deutch, J.M., Forsberg, C.W., Kafak, A.C., Kazimi, M.S., Moniz, E.J., and Pearsons, J.E., 2009. *Update of the MIT 2003 Future of Nuclear Power.* MIT Energy initiative, Cambridge, MS. http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf

Direction du Gaz, de l'Électricité et du Charbon (DIGEC), Direction Générale de l'Énergie et des Matières Premières, Ministère de l'Industrie, var.vols. (1981, 1982, 1984, 1986, 1990, 1993, 1997). Coûts de Référence de la Production d'Électricité d'Origine Thermique (title varies slightly over the years), mimeo, Paris.

Direction Générale de l'Énergie et du Climat (DGEC), Ministère de l'Écologie, de l'Énergie et du Développement Durable, 2008. Coûts de Référence de la Production Électrique. Public summary, Paris. http://www.developpement-durable.gouv.fr/energie/electric/se_ele_a10.htm

ÉDF (Electricité de France), Direction de la Stratégie, 1998. Le renouvellement du parc nucléaire. In: P. Boisson, 1998. Énergie 2010-2020, La Documentation Française, Paris, pp.465–502.

ÉDF (Electricité de France), Études Économiques Générales, var. vols (1972–1994), Coûts de Reference, mimeo, ÉDF, Paris.

Energy Information Administration (EIA), 2009. International Energy Statistics, Electricity Generation. Accessed May 15, 2009.

http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12
Ferrari, A., 1984. French Energy Research Problems in Relation to National Energy Goals. In: B.N. Kursunoglu *et al.* (eds.), Global Energy Assessment and Outlook. Harwood Academic, Chur.
Ferrari, A., 2000. Étude Économique Prospective de la Filière Électrique Nucléaire, Analyse Critique du Rapport. *Revue de l'Énergie* **519**:400–405.
Finon, D., and Staropoli, C., 2001. Institutional and Technological Co-evolution in the French Electronuclear Industry. *Industry & Innovation* 8(2):179–199.
Girard, P., Marignac, Y., Tassard, J (G-M-T), 2000. Le Parc Nucléaire Actuel. Groupe du travail « Cycle Nucléaire, Mission d'Évaluation Économique de la Filière Nucléaire (Annex to C-D-P, 2000). http://www.ladocumentationfrancaise.fr/rapports-publics/014000107/index.shtml
Gravelaine, F., and O'Dy, S., 1978. L'Etat ÉDF. editions Alain Moreau, Paris, France.
Gritsevskyi, A. and N. Nakicenovic, 2000. Modeling uncertainty of induced technological change. *Energy Policy* **28**: 907-921.
Grubler, A. and A. Gritsevskyi, 2002. A model of endogenous technological change through uncertain returns on innovation. In: A. Grubler, N. Nakicenovic and W. Nordhaus (eds) *Technological Change and the Environment*, Resources for the Future Press, Washington DC.
International Atomic Energy Agency (IAEA), Power Reactor Information System (PRIS). http://www.iaea.org/programmes/a2/
Jasper, J.M.,1992. Gods, Titans and Mortals: Patterns of State Involvement in Nuclear Development. *Energy Policy* 20(7):653–659.
Kidd, S., 2009. Nuclear in France – What did they get right? *Nuclear Engineering International* **July 2009:**14–15.
Koomey, J., and Hultman, N.E., 2007. A reactor-level analysis of busbar costs for US nuclear power plants 1970–2005. *Energy Policy* **35**:5630–5642.
Kouvaritakis, N., Soria, A., Isoard, S. and and Thonet, C. Endogenous learning in world post-Kyoto scenarios: application of the POLES model under adaptive expectations, International Journal of Global Energy Issues, Vol. 14, Nos. 1-4, 2000.
Krause, F. and Koomey, J. (with D. Olivier, P. Radanne, and M. Schneider), 1994. Energy Policy in the Greenhouse Volume Two Part 3E: Nuclear Electricity: The Cost and Potential of Low-Carbon Resource options for Western Europe, Study prepared for the Dutch Ministry of Housing, physical Planning and Environment. International Project for Sustainable Energy Paths, El Cerrito CA, USA, mimeo (esp. Section on: Nuclear Costs in France, pp. A.10.10.43-A.10.10.89.).
Lovins, A.B., 1986. The origins of the nuclear fiasco. In: J. Byrne and D. Rich (eds.), the Politics of Energy Research and Development. Transaction Books, New Brunswick, US, pp.7-34.
MacLachlan, A., 1991. N4 Design Review Can't Explain RHR Cracking. *Nucleonics Week* 40(30):7 (July 29, 1999).
MacKerron, G., 1992. Nuclear Costs: Why Do They Keep Rising? *Energy Policy* 20(7):641–652.
MacKerron, G., and Thomas, S., 1986. Why is the Economic Experience of Nuclear Power so Variable? Working Paper, Energy Policy Programme, Science Policy Research Unit, University of Sussex, UK. 13 pp.

Marignac, Y., Dessus, B., Gassin, H., and Laponche, B., 2008. Nucléaire: La Grande Illusion – Promesses, Déboires et Menaces, *Les Cahiers de Global Chance* **25** (October) :3–82. English version at: http://www.global-chance.org/IMG/pdf/G25englishFinal.pdf
McCabe, M.J., 1996. Principals, Agents, and the Learning Curve: The Case of Steam-Electric Power Plant Design and Construction. *The Journal of Industrial Economics* XLIV (4):357–375.
Nectoux, F., 1991. Crisis in the French Nuclear Industry: Economic and Industrial Issues of the French Nuclear Power Programme, Greenpeace International, Amsterdam, *mimeo.*
Rosegger, G., 1991. Diffusion through interfirm cooperation, a case study. In: N. Nakicenovic and A. Grubler (eds.), *Diffusion of Technologies and Social Behavior*, Springer Verlag, Berlin, New York.
(PEON) Commission Consultative pour la Production d'Électricité d'Origine Nucléaire, var.vols. (1973–1979), Rapport de la Commission PEON. Ministère de l'Industrie, mimeo, Paris.
Schlissel, D., and Biewald, B., 2008. Nuclear Plant Construction Costs. Synapse Energy Economics Inc., Cambridge, MA.
Schneider, M., 2008. Nuclear Power: Beyond the Myth. Greens-EFA Group, European Parliament. http://www.greens-efa.org/cms/topics/dokbin/258/258614.pdf
Schneider, M., 2009a. Fast Breeder Reactors in France. *Science and Global Security* **17**:67–84.
Schneider, M., 2009b. Nuclear France Abroad. Mimeo, Paris. http://www.nirs.org/nukerelapse/background/090502mschneidernukefrance.pdf
Schneider, M., 2009c. What France got wrong. *Nuclear Engineering International* August 2009:42.
Thomas, S.D., 1988. *The Realities of Nuclear Power: International Economic and Regulatory Experience.* Cambridge University Press, Cambridge, UK, in particular Chapter 8, France, pp.195–238.
Whitman, Requardt and Associates LLP, 2009. *The Handy-Whitman Index of Public Utility Construction Costs, Bulletin No.168 1912 to July 1, 2008.* Whitman, Requardt and Associates. Baltimore, USA.