Historical Case Studies of Energy Technology Innovation

CASE STUDY 6: NUCLEAR POWER (FRANCE).

THE FRENCH PRESSURIZED WATER REACTOR PROGRAM

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AUTHORS' SUMMARY

The case study reviews the French nuclear Pressurized Water Reactor (PWR) Program as an example of successful scaling-up of a complex and capital-intensive energy technology. 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/y of electricity, or close to 80% of France's electricity production. The institutional setting that enabled a high degree of standardization, external learning via the use of proven US reactor designs under a Westinghouse license, high regulatory stability, and the effective absence of any public opposition are discussed. The case study then considers the economics of this successful scale-up of nuclear reactor technology identifying a significant cost escalation in real-terms reactor construction costs, but also a remarkable stability in reactor operation costs. This is all the more noteworthy considering the need for load modulation in a system relying as heavily on base-load nuclear as is the case in France.

If referencing this chapter, please cite:
Grubler, A. (2012). The French Pressurized Water Reactor Program. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

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/y of electricity, or close to 80% of France's electricity production.

Successful scaling-up of a new technology entails three dimensions: An increase in technology deployment that is a) *substantial* (approaching 80% nuclear electricity), b) *rapid* (50 GWe, or 75% of the total installed capacity of 66 GW 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 all similar 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. Grubler (2009; 2010) provides the first quantitative economic history of the French PWR Program demonstrating that it has exhibited significant escalation in real-term construction costs. This is in stark contrast to the anticipated cost-lowering effects of economies of scale and learning arising from ordering whole series of standardized reactor designs that were at the core of the economic rationale of the French nuclear scale-up. As such the case study illustrates the limitations of both engineering cost projections as well as simplistic learning or experience curve models to describe the cost dynamics of very large-scale, complex technologies

2 INSTITUTIONAL SETTING AS KEY TO SUCCESSFUL SCALING-UP

Following Jasper (1992)'s 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 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*. In other words, "god" (the French government) and the two "titans" that really mattered - the nationalized utility Électricité de France (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, summarized in Table 1.

TABLE 1. OVERVIEW OF FRENCH PWR PROGRAM. NOTES: CONSTRUCTION TIME MEASURED FROM CONSTRUCTION START TO FIRST GRID CONNECTION. SOURCE: GRUBLER, 2009.

order series	reactor type	reactor size typical MWnet (mean MWgross)	number built	constructed between	mean cosntruction time months	mean investment costs "best guess" and (uncertainty range) 1000FF98/kWgross	sites
CP0	PWR Westinghouse licence	900 (927)	6	1971-1979	63	4.9 (4.2 - 5.9)	Bugey Fessenheim
CP1	as CP0	900 (949)	18	1974-1985	65	5.5 (5.0 - 6.0)	Blayais Dampierre Gravelines Tricastin
CP2	as CP1	900 (955)	10	1976-1987	67	6.5 (6.1 - 7.2)	Chinon Cruas St Laurent
P4	1.3 GW PWR Westinghouse licence	1330 (1382)	8	1977-1986	78	6.9 (6.5 - 7.1)	Flamanville Paluel St Alban
P'4	P4 "frenchyfied" Westinghouse	1300 (1366)	12	1979-1993	90	8.4 (8.0 - 8.8)	Belleville Cattenom Golfech Nogent Penly
N4	PWR new French design	1500 (1561)	4	1984-1999	126	11.0* - 13.3 (10.3 - 14.5)	Chooz Civeaux
EPR	EPR Framatome-Siemens	1600 (1650)	1	2007-	under construction	n.a.	Flamanville

* lower range excludes Civeaux-2 reactor

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 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.

The single, most noticed measure of success in the French nuclear scale-up is undeniably the construction times from construction start to first grid connection (see Table 1) and which are short by international standards. While a certain increase across the various successive reactor generations built is evident from the data (IAEA, 2012), 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 compared to 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); around three quarters - 76% of reactors, 70% of gross capacity added - have construction times less than 84 months (7 years), which only a third 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. 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 supplier Framatome); and d) rigorous quality and costs control (that in the words of Boiteux "extends to the beefsteak", i.e. even to the food offered in the canteens on the construction sites).

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 when there was 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 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 in the P'4 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.

3 COSTS OF SCALING-UP

The entire nonmilitary costs of the French PWR Program amounted to some 1.6 trillion (10^{12}) FF98 (constant 1998 French Francs) which translates into 230 billion Euros2008 or 330 billion US$2008 (but not considering any cost escalation after 1998). These cost data come from official French government documents as detailed in Grubler (2009), including especially Charpin et al. (2000) and Girard et al. (2000).

Total costs are split between 810 billion FF98 capital expenditures and 833 billion FF98 operating cost expenditures. The 833 billion FF98 operating cost expenditures are roughly equally split between 402 billion FF98 operation and maintenance costs and 431 billion FF98 fuel costs. Together these translate into total, average levelized systems costs per unit of generated electricity of some 0.2 FF98/kWh for the entire program (Grubler, 2010). This is discussed further below.

The 810 billion FF98 capital expenditures include:

- 480 billion FF98 reactor investment costs plus interest accrued during construction;
- 170 billion FF98 investments and provisions for end-of-fuel-cycle facilities (waste disposal and reactor decommissioning);
- roughly 160 billion FF98 cumulative (public sector, civilian) nuclear R&D expenditures, considered here as knowledge capital investments.

These capital expenditures do not, however, include investments in the fuel cycle facilities, whose amortization and finance are reflected in the fuel costs accounted as operating expenditures. Bataille and Galley (1999) summarize those fuel cycle investments at about 169 billion FF98. About half of these investments relate to the fuel cycle (enrichment, reprocessing, etc.) capacity of the French PWR Program (some 85 billion FF98) with the remainder being covered by foreign clients, presumably for foreign contractual use. Also excluded are expenditures related to the unsuccessful fast breeder reactor, Super-Phénix. Schneider (2009:77) presents French estimates (presumably in current Francs) of some 65 billion FF total lifecycle costs of the 1.2 GW fast breeder reactor.

Specific costs per unit of installed capacity can also be estimated with an uncertainty range as a function of minor uncertainties in construction costs reported across various official documents, inclusion or exclusion of R&D expenditure, and differences in capacity between 65.9 GWgross or 63.1 GWnet. Average specific costs range between 10,400 to 12,800 FF98/kW installed. In US$2008, these numbers translate into a range between 2100 to 2600 US$2008, with lower bound values in both cases being per kW gross capacity and excluding knowledge investments, and the upper bound values being per kW net capacity and including R&D. These numbers do not include any cost escalation after 1998. They also reflect the average costs during the entire program, although as suggested by the lengthened construction times discussed above, actual costs trended upwards during that period.

3.1 Investment Costs over Time

Although the available data do not report investments costs per individual reactor, average annual construction costs over time as well as inferred reactor-specific construction costs can be derived. Details of the method are reported in Grubler (2009; 2010) and consist of combining a constrained vintage-structure optimization model using as inputs both total annual construction expenditures, and typical construction expenditure profiles over construction duration as well as official construction duration data (IAEA, 2012) as constraints in the model calculations to infer average as well as reactor-specific construction costs. The results are summarized in Figure 1 giving “best guess” model estimates as well as estimate uncertainty ranges. (Detailed numerical results are reported in Grubler, 2010).

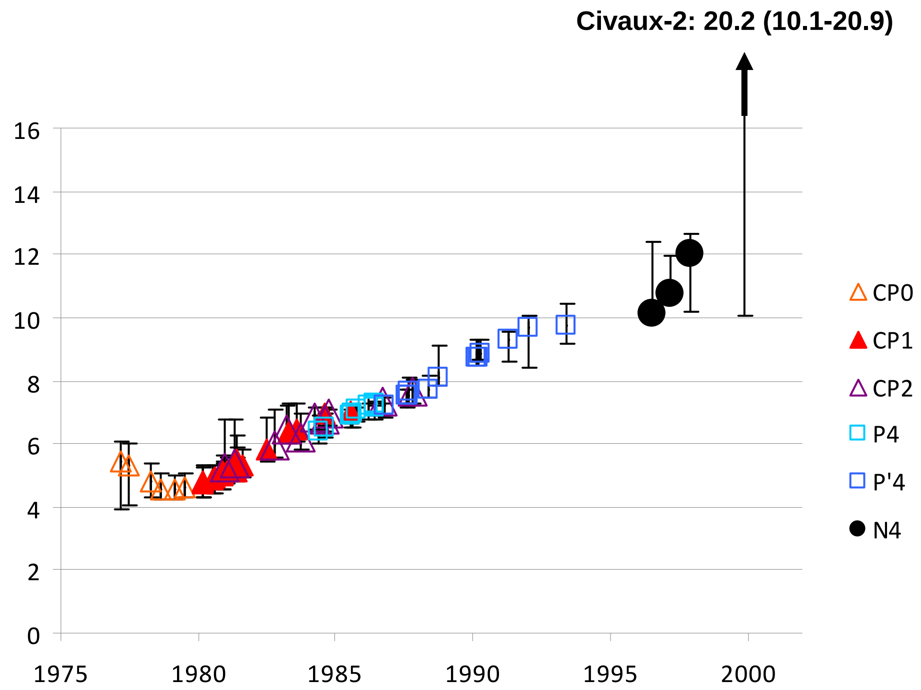

FIGURE 1. SPECIFIC INVESTMENT COSTS OF FRENCH PWRS OVER TIME AND PER REACTOR. NOTES: COSTS SHOWN ON Y-AXIS AS 1000 FF98 PER KW, INCLUDING BOTH BEST GUESS MODEL ESTIMATES (LARGE SYMBOLS, DIFFERENTIATED BY REACTOR GENERATION) AND ESTIMATE UNCERTAINTY RANGES (ERROR BARS). SOURCE: GRUBLER, 2010.

Figure 1 illustrates the substantial real cost escalation of the French PWR program. Even leaving aside the last four N4 reactors (which all exhibit significantly higher construction costs compared to all French reactors built earlier), real-term construction cost escalation across all reactors was both significant as well as substantial: from some 4,000 to 10,000 FF98/kW, i.e. by a factor of 2.5. Including the N4 reactors in the cost escalation calculation reveals an increase by a factor of close to three (but this still excludes the Civaux-2 reactor which was extremely disappointing in terms of cost). This cost escalation, although significantly below that experienced in other countries, most notably the US (cf. Koomey and Hultman, 2007), is far above what would be expected just from longer construction times. The reasons for cost escalation await further detailed research, but have been already alluded to above: loss of the cost-dampening effects from standardization, partly due to up-scaling 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 intellectual capital during the significant scale-back of the expansion program as a result of built overcapacity); and above all, the unsuccessful attempt towards the end of the program to introduce a radically new, entirely French design, the P4 reactor (the precursor to the current European Pressurized Reactor (EPR) design) that did not allow any learning spillovers in design or construction.

The reactor design changes undeniably improved certain safety features (Thomas, 1988; Bataille and Birraux, 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 have been 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 endogenous non-safety drivers of design changes can be summarized simply as: ever larger unit scales and more output (the interest of 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 endogenous 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.

3.2 Operating Costs

Contrary to the substantial cost escalation in construction costs observed in the French nuclear scale-up, operating costs have remained remarkably flat. Since 1984, operating costs have averaged some 0.13 FF98 (or 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. This stability in operating costs, whilst not suggesting any positive learning effects in terms of cost reductions, are nonetheless remarkable considering the increasing need to operate the reactors in load-following mode (and resulting lowered load factors) in a country where base-load nuclear supplies well above three quarters of all electricity generated.

3.3 Levelized total costs

It is instructive to integrate construction (capital) and operating costs over time, e.g. through a customary levelized costs calculation (Figure 2). As noted above, total capital expenditure includes both investment costs as well as decommissioning capital provision. Figure 2 also shows the main components of total levelized costs: the net present value of the cumulative capital and operation & maintenance costs (always until the year reported and discounted with a 5% discount rate). Their sum, divided by the (discounted) cumulative electricity generated yields the average, total levelized costs of nuclear electricity (in FF98/kWh) reported in Figure 2. Also shown are sensitivity analyses with a 0% and 10% discount rate respectively on top of the 5% used in the reference levelized costs calculation. The declining levelized costs should not be interpreted as evidence of some sort of "learning" phenomenon, being instead simply the result of the mathematical formulation of levelized costs that integrate progressively shifting shares of capital and operating costs as the nuclear scale-up program matures. And yet, it allows the opposing trends between significantly escalating construction costs and stable, low operating costs to be put into perspective. With increasing program completion, the escalating construction cost trends are increasingly less important determinants in total levelized costs, which increasingly become dominated by operating costs. Total levelized costs converge to an average value of 0.2 FF98/kWh (equivalent to 0.03 US$98 or 30 mills per kWh nuclear electricity generated), which represents an attractive economic prospect for base-load electricity generation. This even remains the case considering the price escalation beyond 1998 which is not included in these numbers.

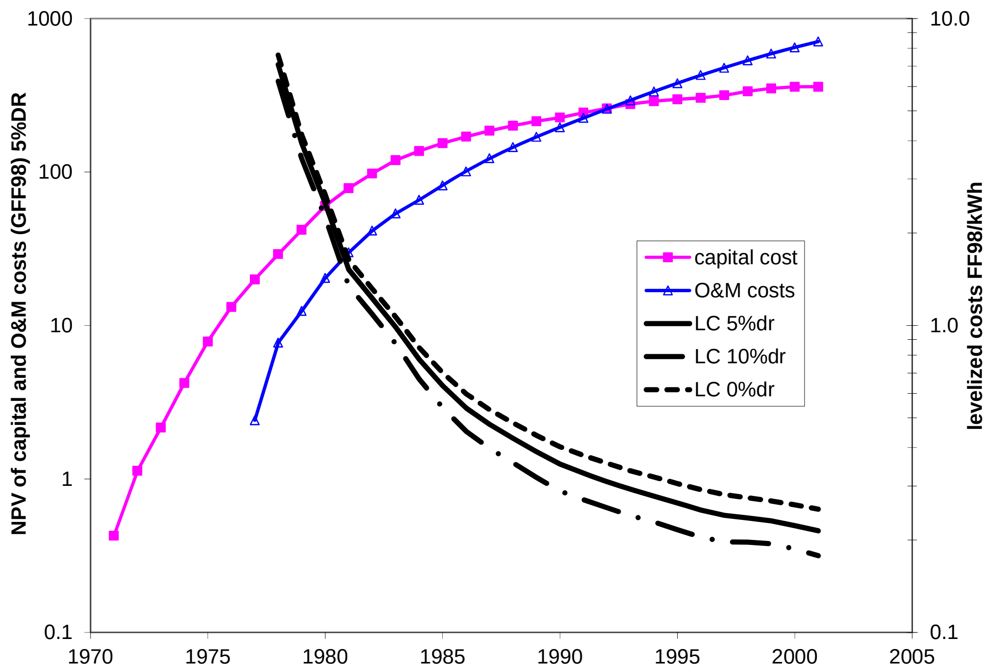

FIGURE 2. CAPITAL AND OPERATING COST COMPONENTS OF TOTAL AVERAGE LEVELIZED COSTS UNDER DIFFERENT DISCOUNT RATES. NOTES: LEFT Y-AXIS SHOWS NET PRESENT VALUE (NPV) OF CAPITAL COSTS (CONSTRUCTION COSTS PLUS DECOMMISSIONING CAPITAL) AND OPERATION COSTS (IN BILLION FF98) UNTIL YEAR REPORTED AND DISCOUNTED AT 5%); RIGHT Y-AXIS SHOWS TOTAL, AVERAGE LEVELIZED COSTS (IN FF98/KWH) OF FRENCH NUCLEAR ELECTRICITY AT 5, 0, AND 10% DISCOUNT RATES (DR).

4 DISCUSSION

4.1 Successful scaling-up

The ambitious French PWR expansion program can be considered the most successful scaling-up of a complex, large-scale technology in the recent history of industrialized countries. The success in terms of rapidity of scale-up, comparatively short construction times, and pervasiveness of diffusion (close to 80 percent nuclear electricity, full fuel cycle industry) arises from a unique French institutional setting that allowed 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.

4.2 Cost escalations & prospects for nuclear

However, the economic assessment of this scale-up yields a more differentiated picture. Despite a most favorable setting, the French PWR program exhibited substantial real cost escalation. Specific investment costs increased by a factor of 2.5 (and by a factor of three when the N4 reactors are included). While this increase is substantially lower than in other countries (most notably the US) it nonetheless raises a number of fundamental issues worth considering with respect to the potential role of nuclear in a climate-constrained world.

If referencing this chapter, please cite:
Grubler, A. (2012). The French Pressurized Water Reactor Program. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

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 investments, and reliant on 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 unit scale. In the history of steam electricity generation, these indeed led initially to substantial cost reductions, but after the 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. As a result, when looking at total levelized costs for the program as a whole, the significant construction cost escalation becomes less and less significant once the reactor expansion program is brought to a successful completion and continues to run at low operating costs. The implication is that nuclear's "valley of death" lies between commercial application and widespread diffusion given 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. This logic may also 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.

Third, this innovation history of the French PWR program 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 if assumptions differ radically from historical experience. An example is given by the assumptions by Kouvaritakis et al. (2000) of substantial cost declines along a learning curve for nuclear reactors. This is counterfactual to even the most successful nuclear scale-up, and results in both biased scenario modeling as well as bad policy advice.

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, complex infrastructure construction projects trend to always cost three 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 combined cycles with carbon capture and sequestration (or very large-scale solar plants in desert areas) could be other prime candidates.

4.3 Negative learning

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 Figure 3 in comparing the French and US experiences.

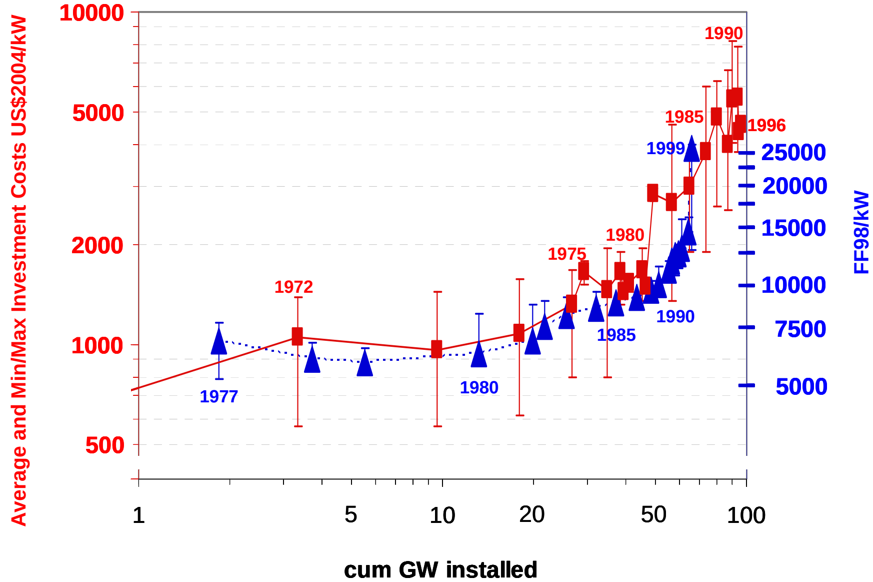

FIGURE 3. REACTOR CONSTRUCTION COSTS PER YEAR OF COMPLETION DATE FOR US AND FRANCE AS A FUNCTION OF CUMULATIVE INSTALLED CAPACITY. NOTES: REACTOR COSTS INCLUDE AVERAGES AND MIN/MAX RANGE. IN BOTH US & FRANCE, NUCLEAR EXHIBITS A PATTERN OF "NEGATIVE" LEARNING DESPITE A RADICALLY DIFFERENT INSTITUTIONAL ENVIRONMENT (CENTRALIZED AND FAVORABLE IN FRANCE, AND FRAGMENTED AND LESS FAVORABLE IN THE US). SOURCE: US DATA FROM KOOMEY AND HULTMAN, 2007; FRANCE DATA FROM GRUBLER, 2009.

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" in the terminology of learning/experience curve models. Note that 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).

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.

5 FURTHER READING

Further details on the innovation histories of nuclear power in France can be found in Grubler (2009; 2010) and in the US in Koomey and Hultman (2007). For additional empirical material and analysis of the French case, see Finon and Staropoli, 2001, and for the French speakers, see also Boiteux, 2009; Girard et al., 2000.

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Grubler, A. (2012). The French Pressurized Water Reactor Program. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.