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# The cost of nuclear electricity: France after Fukushima

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## HIGHLIGHTS

- We compute the levelized cost of French nuclear power over 40 years using a novel court of audit report.
- We include R&D, technology development, fissile fuel, financing cost, decommissioning and the back-end cycle.
- We find a mild capital cost escalation and a high operation cost driven by a low fleet availability.
- The levelized cost ranges between 59 and 83 €/MWh (at 2010 prices) and compares favorably to the US.
- A tentative cost for future nuclear power ranges between 76 and 117 €/MWh and compares unfavorably against alternative fuels.

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ABSTRACT

The Fukushima disaster has lead the French government to release novel cost information relative to its nuclear electricity program allowing us to compute a levelized cost. We identify a modest escalation of capital cost and a larger than expected operational cost. Under the best scenario, the cost of French nuclear power over the last four decades is 59 €/MWh (at 2010 prices) while in the worst case it is 83 €/MWh. On the basis of these findings, we estimate the future cost of nuclear power in France to be at least 76 €/MWh and possibly 117 €/MWh. A comparison with the US confirms that French nuclear electricity nevertheless remains cheaper. Comparisons with coal, natural gas and wind power are carried out to find the advantage of these.



## 1. Introduction

Addressing climate change and energy security within the field of electricity requires methods to compare the cost of alternative technologies (old and new) and their likely evolution. The instrument of choice according to the International Energy Agency (cf. IEA, 2010) is the levelized cost. Capital as well as operation and maintenance are well known and studied across many technologies but assessing the full cost of nuclear powered electricity is a thorny issue because R&D and other development costs are expanded long before commercial operation while plant dismantlement and waste storage will be incurred for decades after electricity generation has ceased.

To construct a robust cost estimator for the entire cycle, a large sample of reactors is required which limits us to the four countries that embarked on the full scale development of nuclear power: USA (101 GW), France (63 GW), Japan (44 GW) and countries from the former Soviet Block ( ≈ 42 GW).[1]

The 1979 Three Miles Island (TMI) accident[2] triggered a scrutinization of the US nuclear power sector. The pioneering study of Komanoff (1981) demonstrates a cost escalation for the construction of nuclear reactors. Koomey and Hultman (2007) follow suit for a large sample of reactors and manage to compute levelized cost for each, finding a strong correlation with the year of commercial operation, i.e., a cost escalation. Oddly enough, they omit to give an overall figure for the US nuclear industry as they favor cumulative distributions to display their results. Since we follow a similar costing method, we are able to adapt their data in order to compare the US to France. Cooper (2011) focuses on safety and pinpoints a regime change after the TMI accident. His econometric analysis shows that increased regulatory pressure leads to longer construction times and therefore greater cost. Whereas cost escalation was mild before TMI, it became more pronounced thereafter.

The 1986 Chernobyl catastrophe has proven that soviet technology (as well as management) was dangerous and is therefore not worthy of study. The 2011 Fukushima disaster revealed that

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[1] We sum capacity from Russia, Ukraine, the Czech republic and Slovakia which are all based on the soviet VVER technology.

[2] We follow the standard terminology of using "accident", "disaster" and "catastrophe" for events of an increasing socio-economic-environmental magnitude; it is applied to TMI, Fukushima and Tchernobyl, respectively.

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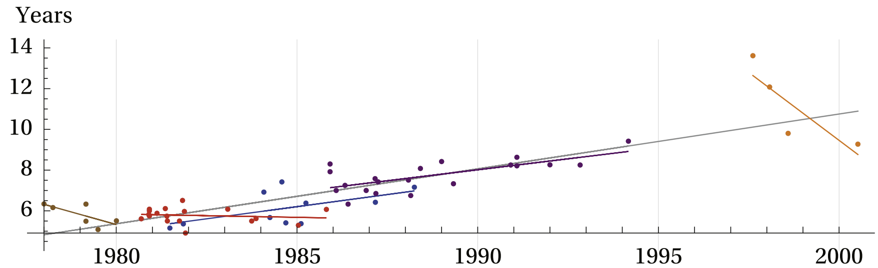


**Fig. 1.** Construction time of second generation French nuclear reactors.

the Japanese nuclear industry was not accident proof and lacked transparency.[3] For long, the French government was equally secretive, but Fukushima "forced" greater transparency. The prime minister ordered a technical audit and asked the Court of Audit (2012) to assess the full economic cost of the nuclear sector. Their report is our main source of information.[4]

After presenting the French nuclear industry, Grubler (2010) studies cost escalation in construction, relying on the first transparency report of Charpin et al. (2000) which did not reveal individual plant cost, but only the yearly investments made by EDF. Based on his estimates, this author finds a strong real-term escalation as well as a stability of operating costs, concluding to a negative "learning by doing". Rangel and Lévêque (2012) use the Court of Audit (2012) report to qualify this finding, concluding that reactors ended up becoming costlier to build; they also find evidence of a learning curve within the same size and type of reactors, confirming the value of standardization.

In the rest of this paper, we take advantage of the newly revealed detailed cost items to assess the economics of the French nuclear power sector as it stands; we also make a prospective incursion into the future as well as a comparison with the US.

## 2. French nuclear program

The first generation of French nuclear reactors designed for commercial electricity generation is developed under the leadership of the *Commissariat à l'énergie atomique* (CEA). Since France lacks uranium mines, a technology frugal on that precious input is pursued at great cost and difficulty. CEA's leadership is contested early on by EDF and the industry heavy weights who push for the US light water technology which is gaining traction around the world. The reasons exposed are, firstly, a greater security of supply for the uranium input, secondly, a wider ability to share future development cost and thirdly, ample market opportunities in the countries under American influence. During the 60s EDF bypasses the prohibition to invest into the Westinghouse pressurized water technology (PWR) by engaging in a joint venture with the Belgian operator who build two such plants. After President *de Gaulle* resigns in 1969, the change is consummated and France licenses the PWR ordering 6 reactors (aka CP0 batch) with construction starting in 1971. A massive order for 18 identical reactors (aka CP1 batch) is then ordered in early 1974 as a consequence of the first oil shock. At the end of 1975, another 18 units are ordered but this time, half of the order corresponds to bigger reactors (CP2 & P4 batches). The final orders are 8 reactors in 1980 (P'4 batch) and 4 in 1984 which dispense from the Westinghouse license and were thus fully French (N4 batch).

Fig. 1 displays the construction time of French nuclear reactors as a function of the date of commercial operation with five distinct colors and linear fittings for the five batches CP0, CP1, CP2, P4 and N4.[5] As indicated by the gray linear fitting over the entire fleet of 58 reactors, there is a clear escalation of construction duration. It is driven by two phenomena. Firstly, there is an escalation between batches (colored clouds do not overlap much) especially with the last one (N4 in orange) which is markedly distinct from the previous Westinghouse models. Secondly, the last Westinghouse batches in blue and purple suffered from a degradation but as shown in the next section, it is not necessarily a sign of higher cost.

## 3. Plant cost evolution

From this point on, we use the information revealed by the Court of Audit (2012)'s report. Like Rangel and Lévêque (2012), we aim to qualify Grubler (2010)'s identification of "negative learning-by-doing in the French scaling up of nuclear power", recalling that he did not have information regarding individual plants or reactors, but only the series of yearly investments made by EDF (cf. his Section 4.3). The auditors detail the capital cost of the 29 plants, each containing two identical reactors as well as all other cost items supported now and then by EDF to build and operate its fleet. In Section 5.1, we use these data to construct a realistic total investment cost for each plant. Since the bundling of reactors by pairs appears a bit artificial, we estimate the cost of each reactor.

The correlation between cost per unit of power at plant level and construction duration for the whole plant is 80%. Likewise, in the US where cost of individual reactors is known, the correlation is 76%. We believe that this strong link between duration and cost warrants the following estimate for individual reactor cost: we split the mother plant cost between the two child reactors in proportion to the construction time of each.[6] Fig. 2 then shows the reconstructed unit cost expressed in 2010€ as a function of the date of first commercial operation.[7] The gray line corresponds to the linear fit over the entire fleet of 58 reactors; it shows an overall limited cost escalation in the sense that the capital cost per unit of power grew at the yearly rate of 2.1% (or 30 €/kW/year), the average cost being 1.5 €/W.[8] This cost containment contrasts with the US where 100 similar reactors were build at prices growing by 19% every year (cf. Section 6.2).

[3] The few Japanese studies on the cost of nuclear power are based on producers accounts and thus fail to capture adequately government R&D expenses and future cost.

[4] Check our draft (Boccard, 2013) for all data and code at http://papers.ssrn.com/abstract=2353305.

[5] The construction time is the lapse of time between the start of construction and the start of commercial operation as recorded in the PRIS database from the International Atomic Energy Agency (IAEA) database.

[6] If a plant has a cost of 100 and it took 4 and 6 years to build the reactors, we assign a cost of 40 to the first and 60 to the second. The case of the last N4 batch of reactors is treated in Appendix B.

[7] Appendix Appendix B explains why we do not use the official date for a few units whose commercial operation was delayed on purpose.

[8] Using construction start instead of operation start, the growth rate would be 2.2% because the period under consideration shrinks. Likewise in the US case, we find 22% vs. 19% if using construction start instead of operation start.