



The Australian National University
Centre for Economic Policy Research
DISCUSSION PAPER

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Fukushima**

Nicolas Boccard
Economics Department, University of Girona, Spain

DISCUSSION PAPER NO. 687

November 2013

ISSN: 1442-8636
ISBN: 978-1-921693-71-7

The Cost of Nuclear Electricity: France after Fukushima

Nicolas Boccard*

September 2013

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 the advantage of these. Our data and code is attached as [excel](#) and [mathematica](#).

Electricity, Nuclear Power, Levelized Cost, Alternative Fuels
JEL codes : L51, H42, D61

*Economics Department, University of Girona, Spain. Email: nicolas.boccard@udg.edu, phone: +34 972 418 719. Financial support from Generalitat de Catalunya (XREPP) and Ministerio de Ciencia e Innovación (contract ECO2010-16353) are gratefully acknowledged. This article was revised during a summer visit to Maria Racionero at the Australian National University in 2013.

1 Introduction

Addressing climate change and energy security in 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 expressing the total discounted cost of delivering electricity from a plant to the grid. 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) accident² 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 lead to longer construction times and therefore greater cost. Whereas cost escalation was mild before TMI, it became more pronounced thereafter. Interestingly, he finds that the largest US nuclear utility, Bechtel, suffered a milder cost escalation, very much like Electricité de France (EDF) as we shall show in this article, confirming that economies of scale require numerous replications of the same plant.

The 1986 Chernobyl catastrophe has proven that the soviet technology was dangerous and is therefore not worthy of study as it will most likely never spread outside its initial area of influence. The 2011 Fukushima disaster revealed that the Japanese nuclear industry was not accident proof and lacked transparency.³ For long, the French government was equally secretive, but Fukushima send a shock wave that “forced” greater transparency.⁴ The prime minister firstly ordered a technical audit with a view to increase security and secondly, asked the [Court of Audit](#)

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

²We 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 resectively.

³The 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.

⁴At the time of the Chernobyl catastrophe, French officials [claimed](#) the radioactive cloud would not pass over the country, then claimed that no public safety action was required when European neighbors were busy taking extreme measures (cf. next footnote).

(2012) to assess the full economic cost of the nuclear sector. Their report is our main source of information.⁵

Beyond providing an excellent introduction to the French nuclear industry, Grubler (2010) performs a worthy study of cost escalation. He relies on the first transparency report of Charpin et al. (2000) which did not reveal individual plant cost, but only the yearly investments by EDF. Grubler (2010) thus estimates those construction costs and identifies 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 article, 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 were developed under the leadership of the *Commissariat à l'énergie atomique* (CEA). Since France lacked uranium mines, a technology frugal on that precious input was pursued at great cost and difficulty. The last closure of this first generation class dates from 1994 and all units are now being dismantled. CEA's leadership was contested early on by EDF and the industry heavy weights who pushed for the US light water technology which was gaining traction around the world. The reasons exposed were, firstly, a greater security of supply for the uranium input (mines in Australia or Canada), secondly, a wider ability to share future development cost and thirdly, ample market opportunities in the countries under American influence. During the 60's EDF bypassed 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* resigned in 1969, the change was consummated and France licensed the PWR ordering 6 reactors (aka CP0 batch) with construction starting in 1971. A massive order for 18 identical reactors (aka CP1 batch) was 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 so that we have the so-called CP2 & P4 batches. The final orders are 8 reactors in 1980 (aka P'4 batch) and 4 in 1984 which dispensed from the Westinghouse license and were thus fully French (aka N4 batch). As recalled in the French Nuclear Security Agency in ASN (2013), plants became more sophisticated which is a basic reason why construction duration and cost may increase.⁶

⁵Like Grubler (2010), who used French official reports before us, we have no evidence, nor reason, to doubt the intellectual rigor of French auditors as further explained in Appendix 7. Our data is available [online](#).

⁶Wrt. CP0, the CP1-CP2 reactors have a different building design, an improved cooling system and more flexible operation. The bigger P4 reactors entail an additional generators to offer a higher cooling capacity, the reactor containment consists now of a double concrete wall instead of a single wall with a steel liner. Lastly, the N4 reactors have more compact steam generators, new coolant pumps and a computerized control room.

The literature has extensively analyzed reactor construction times. Figure 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, N4).⁷ This particular choice of date allows a comparison with a similar graph for unit cost of power in the next section. 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.

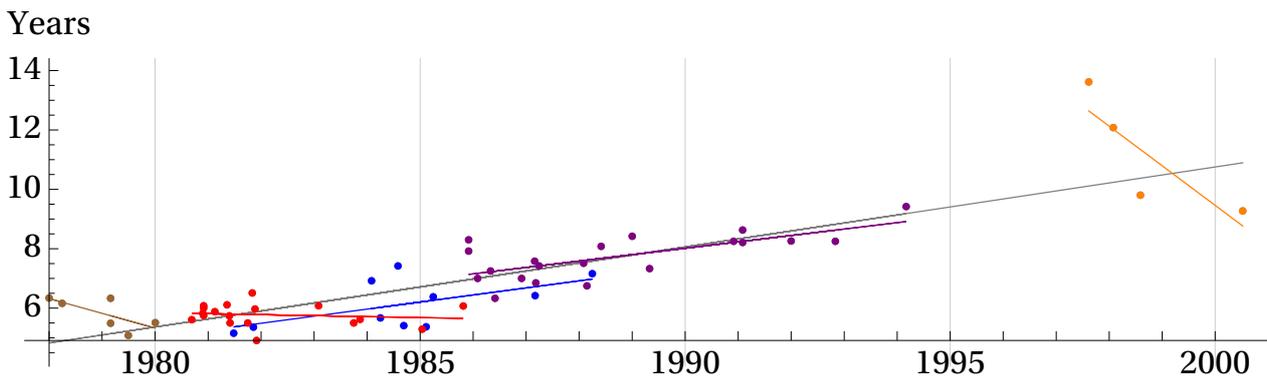


Figure 1: Construction Time of Second Generation French Nuclear Reactors

3 Plant Cost Evolution

From this point on, we use the information revealed by the [Court of Audit \(2012\)](#)'s report. Like [Rangel and L ev eque \(2012\)](#), 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 §4.3).⁸ 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 §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 are known, the correlation is 76%. We believe 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 reac-

⁷The construction 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. Our computer code is available [online](#).

⁸Komanoff (2010) already uses regression analysis over Grubler (2010)'s limited data to obtain a smoother cost escalation of 60% instead of 200%.

tors in proportion to the construction time of each.⁹ Figure 2 then shows the reconstructed unit cost expressed in 2010€ as a function of the date of first commercial operation.¹⁰ 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.¹¹ This cost containment contrasts with the US where one hundred similar reactors were build at prices growing by 19% every year (cf. §6.2).

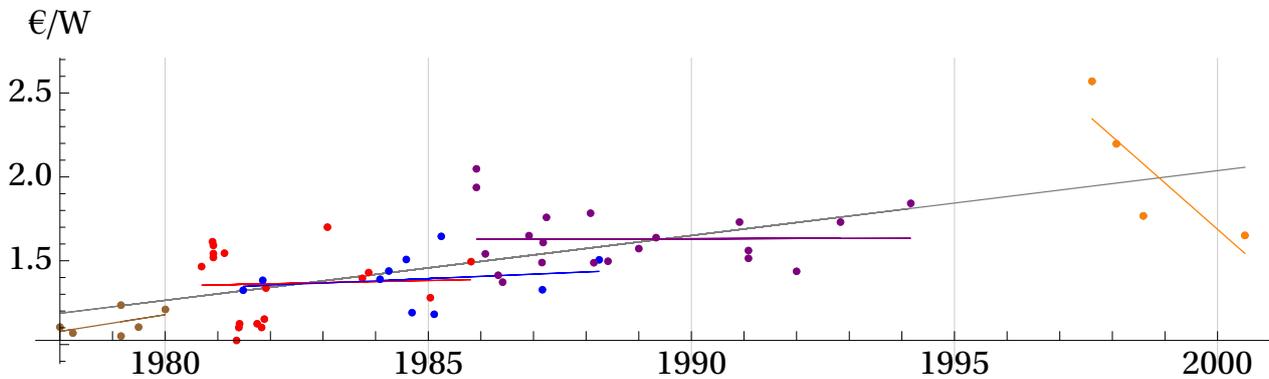


Figure 2: Construction Cost of Second Generation French Nuclear Reactors

We display the five waves of identical reactors with the colors used in the previous section (as well as the corresponding linear fittings). This allows to infer whether there is or no a learning effect in replicating the same reactor. We observe a clear cost escalation with the first batch and a slight one with the next even though construction times improved in both cases. Oddly enough, the same reversal occurs with the fourth purple batch of bigger reactors: their construction times worsened meanwhile they enjoyed a slight cost melioration. These observations obviously need to be qualified by the fact that there is a great variability within all batches and also that non technical constraints may have impacted speed and cost as explained in Appendix 7. All in all, the 48 Westinghouse reactors build during the 1980s (and completed over just 13 years) display an overall great stability with a limited 1.4% yearly growth rate of unit cost. This feat has been ascribed to the standardization made possible by having public monopolies EDF and Framatome focused on dedicated tasks (cf. §3 in Grubler (2010)).

Towards the end of the process, we find the N4 batch of fully French reactors. The Chooz plant, started in 1984, had a total cost of 6.3 bn€ (of 2010). It is about 50% more expensive than the last Westinghouse units but already the second reactor is finished faster than the first so that its cost is most likely to have fallen, as shown on the graph.¹² The last completed plant at Civaux, started in 1988, had a total cost of 4.8 bn€, about a quarter cheaper, so that the unit cost fell from

⁹If a plant has a cost of 100 and it took respectively 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 7.

¹⁰Appendix 7 explains why we do not use the official date for a few units whose commercial operation was delayed on purpose.

¹¹Using 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.

¹²We cannot prove this claim since we have estimated individual reactor costs from build times.

2.15 €/W at Chooz to 1.65 €/W at Civaux, already in line with the unit cost of Westinghouse units. There appears to be a notable learning effect but since we only have two observations, no conclusion should be drawn. It may simply be that the first N4 unit, like all first units, turned out to be more expensive than anticipated whereas the second unit may have achieved the expected cost level. In retrospect, the French nuclear program was an industrial success but its economics were too ambitious and self-centered, having drawn on an expected demand growth that did not materialize due to the oil shocks. Clearly, the full economic benefit could have been achieved with the N4 class of reactors if the output market had been conceived to be the European one in the first place as the sheer size (and cost) of each reactor requires a very large market to achieve scale economies.

To end this section, we compare our estimates to Grubler (2010)'s.¹³ His findings converted to €2010 show an escalation becoming increasingly off the mark especially for the last plant (Civaux) with a 100% error.¹⁴ Figure 3 displays the investment cost per unit of power for all 29 two-reactors plants according to the starting construction date of the first reactor. Grubler (2010) finds a mean of 1.4 €/W (vs. real 1.5 €/W) linearly increasing at a rate of 8.4% (vs. real 2.1%). On the basis of the novel information revealed by the audit, we may thus conclude that Grubler (2010) underestimates the investment cost of the French nuclear fleet but overestimates its rate of growth. The auditors' report thus taught us that French nuclear reactors were dearer than previously thought but also that the scaling up of capacity was achieved while containing cost escalation.

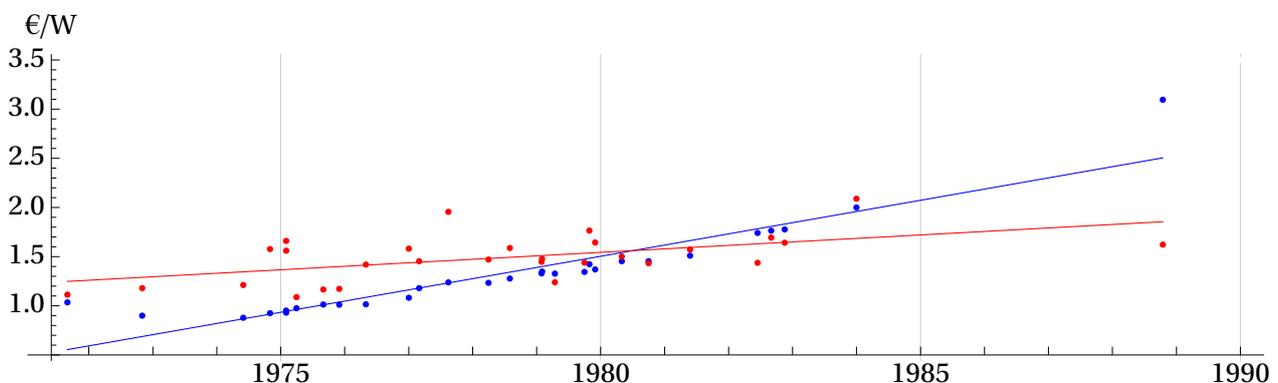


Figure 3: Grubler vs. Court of Audit for Plant Unit Cost

4 Availability & Capacity Factor

This short section looks at the commercial availability of French nuclear reactors as measured by the *capacity factor* (CF), the ratio of actual output to theoretical maximum output. This syn-

¹³ Rangel and Lévêque (2012) do likewise but using solely the cost directly imputed to each plant by the auditors without reallocating the extra disbursement that EDF supported during the fleet construction as we detail in §5.1.

¹⁴We use the 1998 French Francs from the original source since Grubler (2010)'s treatment of inflation appears erroneous. In his paper, 100 FF98 = 13.8 € of 2008 whereas the official deflator of the French economy published by INSEE and the fixed FF/EUR conversion rate indicate a greater 18.4€.

thetic value plays a fundamental role for the computation of the levelized cost. The yearly value shown on Figure 4 is stable enough to allow the computation of a robust estimate. The French nuclear power capacity has been steady at 63.1 GW since 2002 with an average yearly output of 418 TWh, putting the capacity factor at 76%, on average, over the decade, the peak being achieved in 2005 at 78%.¹⁵ This means one in every four reactors which is systemically stopped, for maintenance or any other reason such as an incident. Equivalently, French nuclear reactors run only 18 hours a day, far below the industry consensus for this baseload technology e.g., the US where the capacity factor hovers around 90%.

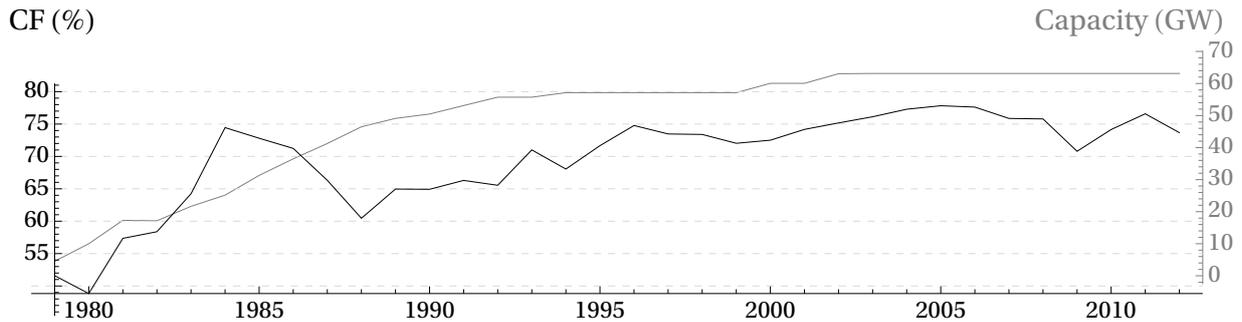


Figure 4: Capacity Factor of French Nuclear Power

In testimony to parliament, EDF ascribes this lackluster performance to a lack of maintenance investments around 2000 which is now inducing frequent failures. EDF has since engaged into an ambitious investment plan to improve reliability.¹⁶ To account for this fact and the likely tightening of security regulation after Fukushima, we add an additional reliability cost item in §5.3 under the “Fukushima” heading. However, we cannot fail to notice from a cursory look at Figure 4, that the capacity factor has been historically low by international standards even during the 1990s when the fleet was young and therefore supposedly problem-proof. A deeper explanation of this phenomena is needed.

A referee suggested a market based one: the low capacity factor may be simply due to a lack of demand, whether national or foreign, thereby forcing the operator EDF to keep some capacity idle. We thus analyze availability data as reported to the transmission system operator over the recent years. As can be seen on Figure 5, the availability of the French fleet, shown in blue, reaches a maximum of about 95% during the winter when demand peaks.¹⁷ During this period of high national demand driven by the extended use of domestic electricity heating, exports are

¹⁵EDF reports a one percent smaller “Design Net Capacity” to the auditors. We nevertheless stick to the value commonly reported in the literature and available from the IAEA or RTE, the French Transmission System Operator. Our output data comes from RTE.

¹⁶cf. fn9 p24 in *Court of Audit (2012)*. Be aware though that this section of the report deals with “industrial availability” which is an upper bound to the CF; in 2006 for instance, EDF claimed availability of 83.6% but achieved a CF of solely $\frac{429 \text{ TWh}}{63.1 \text{ GW}} = 77.6\%$. Furthermore, it would appear EDF uses two distinct definitions at times. Indeed, for 2010, they report a 78.5% industrial availability to the auditors whereas our computation using the daily reports to RTE is only 76.5%.

¹⁷The daily data is smoothed to emphasize the seasonal variation over the day-to-day jumps.

small since the brown and red curves are close. This means that EDF has no cheap spare capacity to sell to neighbors but is technically capable of operating all 58 reactors but three. During the summer, availability falls below 70% to perform plant maintenance, but since baseload falls drastically to half its winter peak, EDF is then able to profitably export the nuclear surplus; graphically the red curve is now clearly above the brown one and close to the blue one. Selecting the four summer months in our sample, we find a 52% correlation between daily availability and the daily mean net exports (totalled algebraically over the six neighboring countries). This shows that when EDF is able to restart a plant, it manages to find foreign buyers. Being a profit maximizing firm, there is every reason to believe that EDF would increase its CF during the summer if it could do so in order to generate profits from exports.

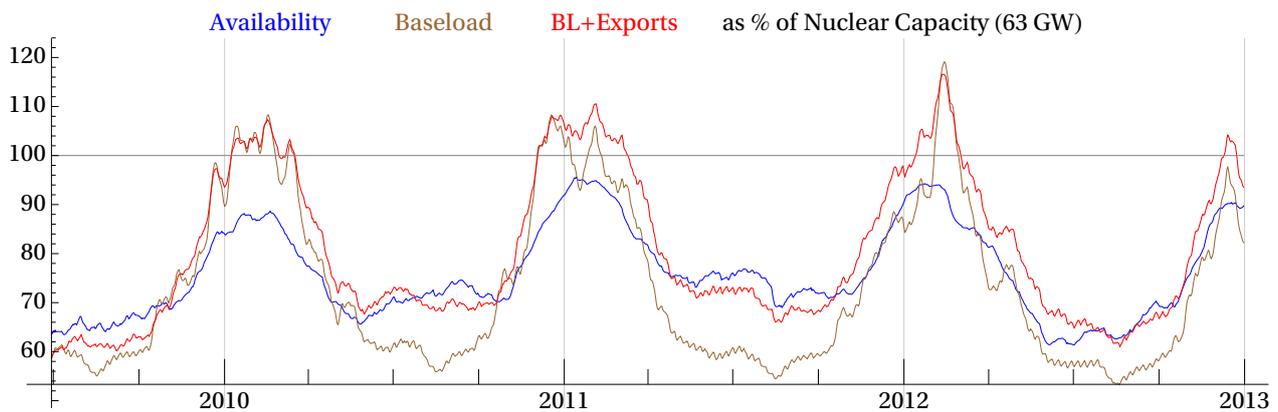


Figure 5: Availability of the French Nuclear Power Fleet

We thus come to the conclusion that the low capacity factor has a technical or organizational origin that EDF has not been able to solve for decades (and is therefore unlikely to improve upon in the future). Whereas the previous section concluded favorably regarding the ability of France to limit investment cost escalation during the expansion of its nuclear fleet, we conclude this section with a note of pessimism: French nuclear power suffers from a rather hidden and indirect weakness as many of its assets are often unavailable to perform their basic duty, electricity generation.

5 Fleet Costing

The [Court of Audit \(2012\)](#)'s report goes back to 1957 when the first plan for civilian development of nuclear power was set up. They only consider civilian expenses related to power generation so that transport and distribution of electricity are naturally excluded. In this section, we look at the entire fleet of 58 second generation nuclear reactors currently in use and explain how the cost items unearthed by the auditors are aggregated into items meaningful for the purpose of computing a levelized cost comparable with foreign experience. All figures are actualized to €2010 to account for inflation.

5.1 Investment

Beyond the direct construction cost of the 58 reactors at about 73 bn€, we find engineering expenses for about 10 bn€ that include management, testing and personnel training.¹⁸ These two items constitute the “overnight cost” of the French second generation nuclear fleet but since reactor construction can last for a decade or more, the interest paid to creditors during construction must be accounted for if we want to be able to compare this technology to alternatives such as wind power or natural gas whose construction time is around a year. To compute this *precommissioning interest*, the auditors assume the needed cash-flow is covered by short-term interest rate instruments and choose the average real rate of French government bonds over the period at 4.5%.¹⁹ They find an extra disbursement of 12.8 bn€. As a matter of comparison and coherency check, we look at the method used in the US for computing *Total Plant Investment* which assumes that the overnight cost will be evenly spread during the period of construction.²⁰ Applying this formula to the French data reveals a financing cost of 13 bn€ quite close to the auditors’ own. Table 1 summarizes the investment cost of the current French fleet of 58 nuclear reactors.

<i>Investment</i>	bn€	€/kW
Construction	72.9	1154
Engineering	10.3	163
Financing Costs	13.0	207
Total	96.2	1524

Table 1: Investment cost (€2010) for French Nuclear Reactors

Beware that Table 1 relates to a mature technology that is not being constructed anymore. Today, IEA (2010) reports the median overnight construction cost of a modern plant to be 4100 \$/kW \approx 3100 €/kW (at the 2010 exchange rate) i.e., twice the past cost. According to EDF itself, the third generation European Pressurized water Reactor (EPR) with a capacity of 1.6 GW being constructed in Flamanville, France, will have a full cost of 8.5 bn€, due to delays and difficulties; as a consequence, the unit power cost will triple wrt. to the second generation at $\frac{8.5}{1.6} = 5312$ €/kW. If we only compare with the most recent units, the N4 batch, whose cost was 1860 €/kW, the EPR still appears quite expensive. This may be due firstly, to the post Fukushima extra se-

¹⁸ Since this amount is only known for the entire fleet, it is imputed to each plant in proportion of its direct construction cost.

¹⁹ A referee suggested the higher 8% used by EDF for its long term evaluations. Although this was the official French public discount rate until 2005, its originator Stoleru (1969) wanted to express the scarcity of capital available for public investment, not its cost. The dominant view today is that of a *social rate of time preference* chosen at 3% in the UK (cf. HMT (2003)) and US (cf. OMB (2003)). In a likewise fashion, the French revision of Lebegue et al. (2005) adopts a 4% rate. Today, the public planning commission (cf. p210 in Quinet (2013)) recommends the exact 4.5% rate chosen by the auditors for energy investments.

²⁰ If 1\$ is spend evenly across n years of construction, an amount $\frac{1}{n}$ is needed in year k . If the creditor is remunerated at the rate r , he is reimbursed $\frac{(1+r)^{n-k}}{n}$ when the plant is ready to operate. Summing over the n years of construction, the total cost of this dollar is $\frac{(1+r)^n - 1}{rn} > 1$ which is the multiplier accounting for the duration of construction.

curity requirements and secondly, to the high learning cost of building the first unit of a novel technology, after of a decade of interrupted construction with the ensuing loss of know-how. A more heterodox explanation would be that “hidden development cost” previously buried into the state’s accounts are now exposed thanks to the greater transparency requirements of public works construction.

5.2 Fuel

The uranium fuel cycle involves three stages. The front-end consists of extraction, conversion and enrichment all of which are covered by AREVA, the French monopoly fuel producer (formerly COGEMA). As reported by the auditors, EDF has a “cost plus” agreement with AREVA. The invoice for enriched uranium over the last tree years has been stable around 1.5 bn€. The court of auditors points to the fact that AREVA is a profitable endeavor to assume that this price high enough to recover past investments and face future dismantling cost.²¹ As a consequence, we exclude investment related to fuel fabrication from the table in the previous section.

During the second stage, the enriched uranium is burnt in reactors for about 4 years before entering the third stage called the back-end cycle.²² As a consequence, after 4 years, a reactor produces a steady amount of spent fuel so that EDF, with its fleet of 58 reactors, is facing a continuous flow of spent fuel. For that reason we differ from the auditors in choosing to treat “spent fuel” as an operating expense rather than a part of the back-end cycle.

To assess this recurring cost, we use the fact that the current stock of spent fuel is 18.6 kton and its future treatment cost is estimated by auditors at 14.8 bn€. Based on information relative to 2008, 2009 and 2010, EDF consumes on average 1.13 kton of fuel per year (and generates as much spent fuel), it incurs a mean yearly “spent fuel” expense of $\frac{14.8}{18.6} \times 1.13 \approx 0.9$ bn€.²³ As shown in Table 2, EDF also incurs a cost of keeping fuel stocks that has been rising up to 0.6 bn€/year.

<i>Fuel</i>	bn€/year
Acquisition	1.5
Spent fuel	0.9
Stock	0.6
Total	3.0

Table 2: Fuel cost (€2010) for French Nuclear Reactors

²¹Past investments on enrichment and reprocessing amount to 40 bn€ while dismantling is estimated to cost 7 bn€.

²² This latter involves first some 12 years of cooling in pools before recycling. At the moment, some 16% of the fuel used in French reactors comes from recycling. The remains waste then enters long term storage.

²³Auditors find the larger 1.1 bn€ figure looking solely at the 2010 accounts.

5.3 Operation & Maintenance

Table 3 summarizes all the elements entering the variable cost of nuclear power generation found by the auditors in EDF's accounts for 2008, 2009 and 2010. We use the latest values from 2010 as there is stability across all lines. Maintenance gathers two distinct charges that are entered at one place as cost (2095 M€) and elsewhere as investments (1747 M€). We also take into account, under the Fukushima label (2000 M€), of the stated desire by EDF to ramp up investments, firstly to meet more stringent security requirements and secondly, to reach a 80% capacity factor by improving reliability. Labour includes wages (2042 M€) and the many perks enjoyed by employees (634 M€). Support include central services (932 M€), taxes (1176 M€), research (644 M€) and financial cost (626 M€). Even in the absence of the special Fukushima charge, O&M weights almost 10 bn€ each year, thrice the cost of fuel. This is unusually large when compared to international studies.

<i>O&M</i>	bn€/year
Maintenance	3.8
Labour	2.7
Support	3.4
Fukushima	2.0
Total	11.9

Table 3: Variable cost (€2010) for French Nuclear Reactors

5.4 Back-end Cycle

For our purpose, the back-end cycle regards solely the dismantling of power plants at the end of their operating life and waste management since we treat spent fuel as an operating expense. The auditors recognize that evaluating the back-end costs is a complicated exercise, necessarily based on many assumptions, among which the discounting of these far away future outlays. France is already in the process of performing these tasks but none relative to the first generation reactors is yet completed. The official policy is immediate dismantling to avoid burdening future generations and take advantage of industrial know-how. According to [Court of Audit \(2005\)](#), the technical schedule assumes a first 10 years phase of deconstruction followed by a 15 years waiting period before the third 10 years phase of site restoration. The schedule of nominal expenses is thus spread over more than two decades and is therefore much larger than its present value at the time of plant shutdown. The dismantling cost figures shown hereafter deal solely with second generation reactors and active ancillary facilities still from the CEA.

EDF initially followed the official recommendation of using the overnight cost as a reference for estimating the dismantling cost. The rate hovered over 15% and has been now adjusted at 19% which puts the fleet dismantlement at 18.4 bn€ or 290 €/kW. Based on the experience gained in the process of dismantling the dozen first generation facilities, EDF has developed an alternative method regarding a plant with four 900 MW reactors, arriving at a unit cost of 267

€/kW (or 320 €/kW if we add the uncertainty factor of 20% recommended by the auditors). Unsurprisingly, EDF’s dismantling cost estimate is the lowest among international peers. It is 50% more in Belgium, 100% more in pre-Fukushima Japan and 150% more in the UK and Germany. The first ever PWR reactor to be actually dismantled was the “Maine Yankee” at a unit cost of 520 €/kW i.e., about twice EDF’s estimate (cf. table 4.5 in [Nuclear Energy Agency \(2004\)](#)). These discrepancies justify a “worst case” scenario in the summary section where the dismantling cost is doubled.

The research arm of the French nuclear industry, CEA, has also a number of support facilities whose total dismantling cost is estimated to be 3.9 bn€. Since half are still in activity, we assign half of the aforementioned cost to our back-end cycle. Lastly, an oft forgotten item is the non irradiated fuel inside the reactor at shutdown. The disposal of these “last cores” is expected to cost 3.8 bn€ thereby raising the dismantling bill to at least 24 bn€. The ratio to investment cost for the French nuclear fleet will thus be a minimum of 25% which is much higher than the standard 15% still used by [IEA \(2010\)](#); a revision of this figure is therefore in order.

Lastly, the long-term management of radioactive waste i.e., deep geological disposal is a highly uncertain undertaking since none has been constructed yet on earth; the auditors thus follow the estimates being made by EDF (23 bn€) and CEA (2.4 bn€), noting that an alternative estimate from ANDRA, the French National Radioactive Waste Management Agency as well as international ones are about twice larger. Once more, this alternative will be reflected in the “worst case” scenario where such cost is doubled. Table 4 gather the items previously discussed.

<i>Back-end</i>	bn€	€/kW
Dismantling EDF	18.4	291
Dismantling CEA	1.9	30
Last cores	3.8	60
Waste EDF	23	365
Waste CEA	2.4	38
Total	49.5	784

Table 4: Back-end Cycle Cost (€2010) for French Nuclear Reactors

5.5 Provisions for the Future

The previously cited reports on dismantling and waste management were tasked with estimating the future cost of these activities on the implicit assumption that the process would start immediately. However, the levelized cost of nuclear power we are looking for in this article relates to a plant whose operation would start now so that the back-end cycle would only start after 40 years, the plant lifetime generally assumed in the literature. The nuclear operator thus needs to provision an amount x every year to be able to meet his back-end commitments when the time comes. Given the interest rate r that a prudent investment will fetch, the final accumulation will be $x \sum_{k \leq 40} (1+r)^k$. The provision is thus a proportion $x = \frac{r}{(1+r)((1+r)^{40}-1)}$ of the requirement.

French operators EDF and AREVA use a nominal 5% rate which given inflation is akin to 3% in real terms, a figure similar to other European nuclear operators.²⁴ The auditors criticize their choice because the inflation for building and especially underground work seem to outpace the general rate and also because a prudent nominal rate of 5% need not hold for the decades to come. For that reason, we lower the real interest rate to 2% which puts the provision at 1.6% of 49 bn€ or .8 bn€/year.

Given the risk underlying the nuclear sector, the [Court of Audit \(2012\)](#) as well as the [Senate \(2012\)](#) recommend to add an additional 4 bn€ yearly insurance premium to cover damages up to 100 bn€ in case of a major accident. The proposed insured amount is the economic damage of hurricane Katrina, the second costliest ever natural disaster after the 2011 Japan Earthquake whose damage is estimated by [MunichRe \(2013\)](#) at 160 bn€.²⁵ This additional item puts the yearly expense above 6 bn€ in the worst case scenario. All in all, the future liabilities of nuclear power can rise up to a significant 15€/MWh on levelized terms.

The yearly insurance premium stands at 69 M€ per reactor (\approx 91 M\$ at the 2010 exchange rate). This is a major sum when compared to current practice. In most European countries, nuclear operators only need to cover 700 M€ of damages while their government covers an additional equivalent amount through an international convention. In the US, the Price-Anderson Nuclear Industries Indemnity Act is more generous as it covers up to 13 bn\$ for a single accident (but the country also host more reactors, thus a greater risk). Nevertheless, the yearly premium paid by US nuclear operators per reactor is a hundred times less what the market would ask to cover the economic damages of a major accident.²⁶

5.6 Development Cost

As noted by the auditors, the deployment of the existing nuclear sector was preceded and supported by major research programs which may be regarded as a long lived investment into intangible knowledge. Entirely public and centralized at the start in the 1950s, funding was progressively decentralized and privatized. Most of this R&D happened many years before the nuclear electricity generation occurred so that the present value is considerably larger than the nominal one. A relatively stable yearly R&D expense of 1 bn€ in real term is observed from 1957 until 2010, leading to a total of 55 bn€.²⁷

One could argue that R&D relative to the third generation of reactors (aka fast breeders) which is not yet active should not be counted but we take the view that EDF spends into R&D every year to maintain and develop its knowledge base; it must therefore cover those expenses from its current revenues, just like any other business. A special mention must be made for the

²⁴Since plants have on average 15 more years of operation, EDF values its future commitments at $(1.05)^{-15} \approx 50\%$ of the amount seen above. It then sets aside about 5% of this amount every year.

²⁵In relation to that event, the July 2013 estimates for cleaning up Fukushima are 20 bn\$ for the site and about as much for the surrounding areas.

²⁶[Horin \(2012\)](#) reports that the consortia of American Nuclear Insurers quoted yearly premium in 2011 of 0.9, 1.3 and 1.8 M\$/year for plants with one, two or three reactors; the average over the the entire fleet of active US reactors is 0.7 M\$ per reactor i.e., one hundredth of the cost of covering a Katrina type disaster.

²⁷The R&D on the fourth generation of fast neutron reactors is 3.1 bn€. It is left out, being a distant project.

failed [SuperPhénix](#) project which started as an European industrial endeavor on fast neutron reactors but ended up in the hands of EDF. This problematic plant produced for some time but had to be prematurely shutdown; its full actualized cost is estimated at 12 bn€. We have also decided to count the full cost of the first generation reactors (6 bn€) treating them as a training for the nascent French nuclear power industry. After adding the dismantling cost of these early reactors, we arrive at a grand total of 77 bn€ shown in Table 5.

<i>Development</i>	bn€
R&D 1st gen	14.4
R&D 2nd gen	20.0
R&D 3rd gen	21.0
SuperPhénix	12.0
Old Reactors	6.1
Dismantling	3.9
Total	77.4

Table 5: Developmental Cost (€2010) for French Nuclear Reactors

This *developmental cost* is spread uniformly over the cumulative nuclear power output from 1968 until 2010; it includes 391 TWh from first generation reactors and 9691 TWh from the current fleet leading to a levelized *developmental cost* of 7.7 €/MWh.²⁸ This noteworthy cost item may partly explain why the novel EPR appears so expensive to build for there is nowadays less scope to bury such development cost into public accounts.

5.7 Summary

To express the cost of French nuclear power in a levelized form, we need to turn the cost of both construction and back-end cycle as yearly disbursements over the asset lifetime. The interest rate choice is crucial. In France, [Quinet \(2013\)](#) recommends 4.5% for publicly financed energy investments. In the US, [Koomey and Hultman \(2007\)](#) used the average real return on investment at 5.7% rounded to 6%. Lastly, the international comparisons of [IEA \(2010\)](#) are based on a 5% rate which we retain for our “best case” scenario where future cost behave as expected.

The “worst case” scenario then uses future cost that are twice greater and a 10% interest rate to reflect the switch to an investor owned business that would be financed solely by private lenders (without State guarantees). This has two consequences. Firstly, given the amortization period of 40 years, the respective annuity (aka fixed rate mortgage payment or capital recovery factor) jumps from 5.8% to 10.2% and secondly, the cost of interest paid during construction also increases. We thus use the 23 bn€ value computed by EDF for its pre commissioning interests instead of the 13 bn€ computed by the auditors.

²⁸The second generation data in the auditors report comes from EDF while we reconstructed the output of the first generation fleet. It should be noted that this cost will fall to 6.1 €/MWh in 2020 by a simple amortization effect if R&D is maintained at 1 bn€/year and the yearly electrical output also remain stable.

In Table 6 below, the first column contains the aggregate annuity for each item. The second column then offers a unit cost in €2010 per kW. The last column then uses the yearly output of the French fleet (equivalently the capacity factor) to derive a cost per MWh of energy produced. Note at this point that the low 76% historical availability rate of the French nuclear fleet weights negatively on cost.

<i>Frecnh PWR</i>	<i>Best</i>			<i>Worst</i>		
Item	bn€/y.	€/kW/y	€/MWh	bn€/y.	€/y./kW	€/MWh
Capital	5.6	89	13.4	10.9	172	26.0
O&M	11.9	188	28.5	11.9	188	28.5
Fuel	3.0	48	7.3	3.0	48	7.3
Back-end	0.8	13	1.9	1.6	25	3.8
Insurance				4.0	63	9.6
Development			7.7			7.7
Total	21	338	59	31	497	83

Table 6: Levelized Cost of French Nuclear Power

What stands out from the best case is O&M which weights more than half of the yearly cost, thus dwarfing the capital cost. Nuclear is generally touted as a technology with expensive investment but with low variable cost. In the French case, it would appear that EDF may have been efficient at building the plants but has proven feeble to maintain them. It seems to suffer the typical public monopoly ailment of uncontrollable cost inflation. The third column shows the impact of the low capacity factor which mechanically increases all levelized items. In the worst case scenario, all items except O&M increase and each becomes meaningful, thereby contributing to a high cost of generating nuclear electricity for the French people. In a nutshell, past nuclear electricity in France is at best as cheap as the market price commonly observed in Europe (≈ 60 €/MWh) but may turn out to become a third more expensive (≈ 80 €/MWh) if the premiums related to future liabilities become binding (remuneration of capital, accident, waste management).

The government has set the nuclear electricity tariff at 42 €/MWh in 2012 following the recommendation of [Champsaur et al. \(2011\)](#) who forecasted the cost of running the current nuclear fleet over the next 15 years at 39 €/MWh. We can thus compare our findings to these. The evaluation of yearly operation expenses and maintenance investments at 14 bn€ is close to ours while the yearly cost of the back-end cycle stands at 0.8 bn€ a 25% discount wrt. our own figure. The main difference lies in the treatment of past investment as these authors estimate from the way regulated tariffs were build by EDF that the unamortized part of the fleet is only 15 bn€, leading to a yearly provision of 1.8 bn€,²⁹ about a third of the true cost of capital under cheap public financing (5.6 bn€). The discrepancy can be thus ascribed to a different horizon insofar as they discard both the past and the far away future. Another way to look at the unamortized

²⁹The interest rate is set conservatively at 8.4% and since the regulation lasts for just 15 years, the annuity rate is a large 12%.

value is to use the fleet’s age, 26 years in 2011 when the report was issued, and compute the proportional unamortized investment as $\frac{40-26}{40} \times 96 \approx 34$ bn€ which means that French customers have been charged in the past more than their fair share of the capital cost of nuclear reactors.

At the outset of this section, we compare our findings with Grubler (2010) in Table 7 to understand how the novel information revealed by the Court of Audit (2012) changes our perception of the cost of French nuclear power. Grubler (2010)’s overall estimate for the construction cost is in the ballpark of ours. Next, he finds an operational expenditure spread over three decades which translates into a yearly expense which is only a quarter of our finding. This may be due either to a lack of information (hidden items) or to an escalation of EDF’s cost as our estimate is based on recent years only. His fuel cost spread over three decades translates into a yearly expense slightly below ours. For the back-end cycle, he identifies a need that is one half of our own. This fact is readily explained by the constant upward revision of estimates for this future activity. For R&D development, his total builds on the figures revealed by previous studies up to 2000 and incorporate solely the first and second generation R&D.

Item	Capital	O&M	Fuel	Back-end	Development	Total
Grubler	12.5	6.0	6.3	2.5	3	30
Auditors	13.4	28.5	7.3	1.9	7.7	59

Table 7: Levelized Cost in €/MWh of French Nuclear Power

A first obvious inference from this basic comparison is that many cost items relating to nuclear power were still hidden and each contributes to inflate the final bill. Using our method for spreading investments over the years, Grubler (2010)’s cost information translate into a yearly cost of capital (expressed in €/kW/y) that is just one half of ours and an extremely competitive levelized cost of 29€/MWh. A strong conclusion therefore emerges: thanks to the Court of Audit (2012) report, the objective estimate of the full cost of the French nuclear power program has been revised upwards by a factor two.

6 Comparisons and Extensions

6.1 Future Nuclear Electricity ?

The figures shown in Table 6 relate to a past technology and should not therefore be used to assess future cost. However, we can use the latest official estimates of the Flamanville EPR cost at 5.3 €/W, to compute a tentative future cost.³⁰ We leave aside the development cost that has been carried by French tax payers over six decades and set an improved commercial availability (aka CF) rate at 85%, in line with international best practice. Otherwise, we maintain the same cost for O&M, fuel procurement and the back-end cycle since the operator, EDF, is unlikely to be able to change its operational culture for some time. From that point on, we build two scenarios as before assuming for the worst case that future cost and the interest rate are doubled. We

³⁰This revised estimate now lies at the median of IEA (2010)’s international sample. Note also that it is not an overnight cost since the delays in construction are incorporated.

observe from Table 8 that the capital cost weights heavily on the final result making the back-end cycle and catastrophe insurance small in comparison since they only weight about 10% of the final bill. Those in favor of nuclear power can therefore realistically claim that an almost perfect security in the back-end cycle can be funded. This may be the reason why some NGOs are now pursuing a novel opposition strategy, namely emphasizing the cost of building nuclear power plants (at least in developed countries).

<i>EPR</i>	<i>Best</i>			<i>Worst</i>		
	bn€/y.	€/kW/y	€/MWh	bn€/y.	€/y./kW	€/MWh
Capital	19.5	310	41.6	34.3	543	73.0
O&M	11.9	188	25.3	11.9	188	25.3
Fuel	3.0	48	7.3	3.0	48	7.3
Back-end	0.8	13	1.7	1.6	25	3.4
Insurance				4.0	63	8.5
Total	35	559	76	55	869	117

Table 8: Tentative Assessment for Future Nuclear Power

To conclude, our projection reveals that the issue with nuclear power today remains its most basic economic characteristic, capital cost. Interestingly, the October 2013 deal between EDF and the UK for an EPR reactor includes a guaranteed price of 108 €/MWh over 35 years, which, according to [Harris et al. \(2013\)](#), should award EDF with a 10% return on investment. This would put EDF levelized cost at about 98 €/MWh, in between our scenarios. Should this agreement carry on, it will send a clear message regarding the cost of nuclear power (in Europe at least).

6.2 US vs. France

The importance of nuclear power in the US warrants a comparison with France. We use [Koomey and Hultman \(2007\)](#)'s cost data together with the latest [IAEA](#) capacity factors. Figure 6 is based on the 99 plants covering 95% of total capacity for which these authors could find cost data; it displays the escalation in capital cost (total plant investment in \$2010) as a function of the commercialization date. The average cost was 3401 \$/kW or about twice the cost of nuclear power plants in France using the US-FR PPP exchange rate of 2010 at 1.15 \$/€. Based on a linear fitting, we may say that on average, for every year that passes, the completion of a new plant will cost an additional 387 \$/kW; equivalently, the mean yearly cost increment was 19%.

Limiting ourselves to the 104 reactors active at the end of 2012, Figure 7 shows the march towards the current 100 GW of installed capacity and the evolution of the capacity factor towards an all-time high of 92% in 2004 followed by a reversion towards 86% in 2012, a level notably higher than in France.

[Komanoff and Roelofs \(1992\)](#) already incorporated the development expenses into the levelized cost for the US nuclear power sector over the period 1950-1990. They find that utilities expended 514 bn\$ (of 2010) for construction, operation, fuel and dismantling, 72 bn\$ on cancellation and waste management while federal subsidies (e.g., R&D, tax breaks) amounted to 124

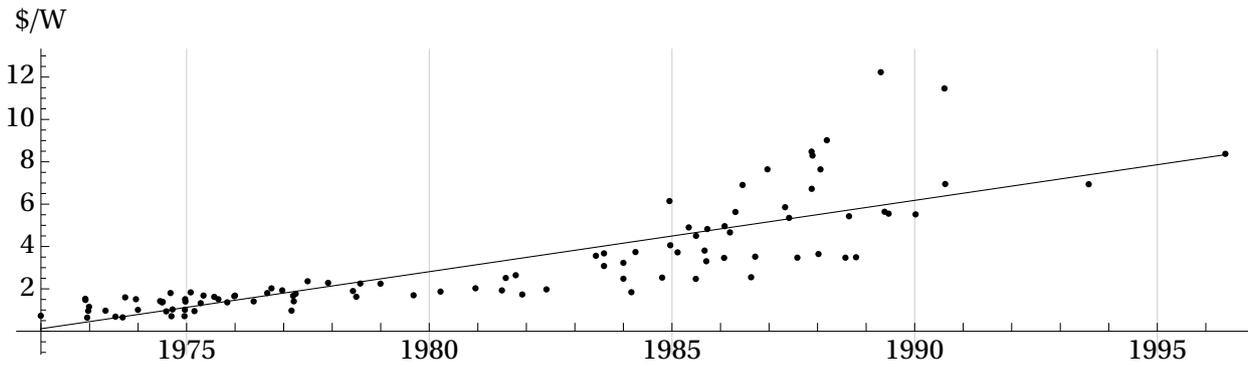


Figure 6: US PWR reactors construction cost

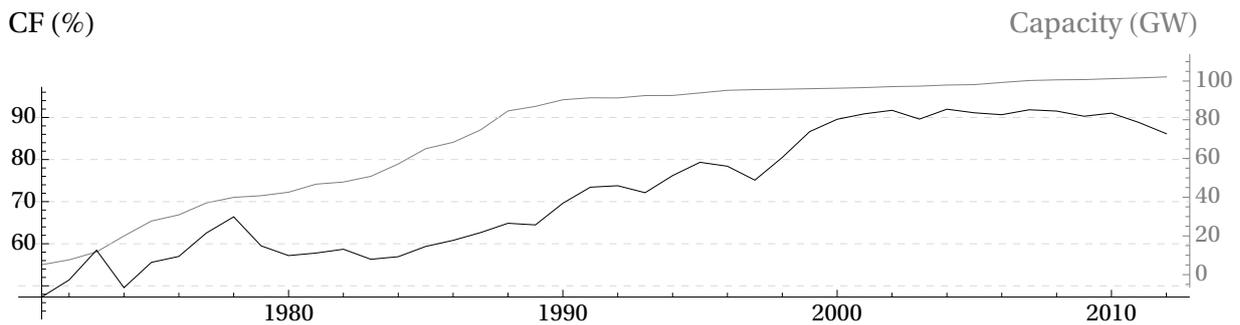


Figure 7: US active reactors

bn\$. Taking into account the nuclear electricity produced from 1968 until 1990 (5369 TWh), the levelized cost stood at a high 132 \$/MWh. During the two decades since this pioneering study, twice the amount of energy has been produced in those nuclear plants while federal subsidies have dwindled. The Energy Information Administration (EIA) has reported on this topic for the years 1992, 1999, 2007 and 2010. On average, the nuclear sector received 1.6 bn\$ per year, so that a minimum of 32 bn\$ of subsidies should be assigned to the period 1991-2010. Repeating the previous calculation over the longer period, we find that the development cost is better amortized at 9.5 \$/MWh instead of 23 \$/MWh.

To allow a direct comparison with the French levelized cost, we reassign the cost elements of [Kooimey and Hultman \(2007\)](#) into similar categories, set the interest rate at 5% instead of 6%, convert \$2004 into \$2010 using the US GDP deflator and then into Euros. In [Table 9](#), we derive a “best case” levelized cost of US nuclear power.³¹

Looking the global amount in the first column, we see a bit unexpectedly that capital only weights one half while O&M grabs a third of the total cost. The capital cost escalation that the literature has previously identified is thus accompanied by an operational cost overrun probably engendered by the absence of cost cutting incentives in the US regulatory compact. Once the large cost of developing civil nuclear power is integrated in the last column, the levelized cost reaches 75 \$/MWh. This is only a tenth higher than in France since the twice larger capital cost

³¹ Note that we do not correct for the fact that US reactors are, on average, at least one decade older than their French counterparts.

<i>US</i>	bn\$/y	\$/kW/y	\$/MWh	<i>US</i>		<i>FR</i>	
				€/kW/y	€/MWh	€/kW/y	€/MWh
Capital	22.7	227	33.4	198	29.0	89	13.4
O&M	15.1	151	22.2	131	19.3	188	28.5
Fuel	5.5	55	8.1	48	7.1	48	7.3
Back-end	0.9	9	1.4	8	1.2	13	1.9
Development			9.5		8.3		7.7
Total	44	443	75	385	65	338	59

Table 9: Levelized Cost of US Nuclear Power

is largely compensated by the relatively lower cost of operation. Fuel cost the same while the US back-end cycle is unrealistically low since firms's provisioning was devised at least a decade ago and did not take into account the novel security requirements that have appeared since.³² The cost of developing nuclear power (on a per MWh basis) is larger in the US than in France but it is probably better to look at it the other way around. The licensing of the US technology in 1968 saved France the cost of developing a new technology from scratch, At the same time, France spend a total of 88 bn\$ while the US, a country five times more populous and seven times richer, only spend 156 bn\$ i.e., twice more. In the end, the small player was able to better amortize its greater national effort because it went "all out" for nuclear, managing to cover three quarters of electricity demand with this particular technology.

6.3 Comparison with Coal and Natural Gas

Coal is the alternative dominant technology for generating baseload electricity, making a side by side comparison quite relevant. The long and documented history of coal powered electricity in the US has allowed [McNerney et al. \(2011\)](#) to derive a chronicle of levelized cost over a century, shown on Figure 8.³³ Using their data, we are able to check that coal powered electricity achieved a mean levelized cost of 52 \$/MWh over the period 1968-2010 making the nuclear alternative at 75\$/MWh some 44% dearer.

Looking at future construction and using something akin to a 10% interest rate on capital, an MIT team found nuclear to be 56% more expensive than coal in 2003 (74\$/MWh vs. 47\$/MWh); an update of the same study (without carbon tax) finds a reduced 35% wedge with 84\$/MWh vs. 62\$/MWh (cf. [MIT \(2009\)](#)). Official sources such as [IEA \(2010\)](#) tend to find lower figures for nuclear technology as they use low discount factors and several optimistic hypothesis feeded to them by operators. Removing the carbon tax, median figures are 50\$/MWh for coal and 65\$/MWh for nuclear (+30%).

³²Once more, this omission is harmless since discounting weights so heavily on future expenses; the proper accounting of back-end cost would only hinge slightly on total cost.

³³ There was an absence of coal power plant construction during the last decade forcing us to reconstruct cost data using the uninterrupted retail price series and the almost constant absolute profit margin that prevailed.

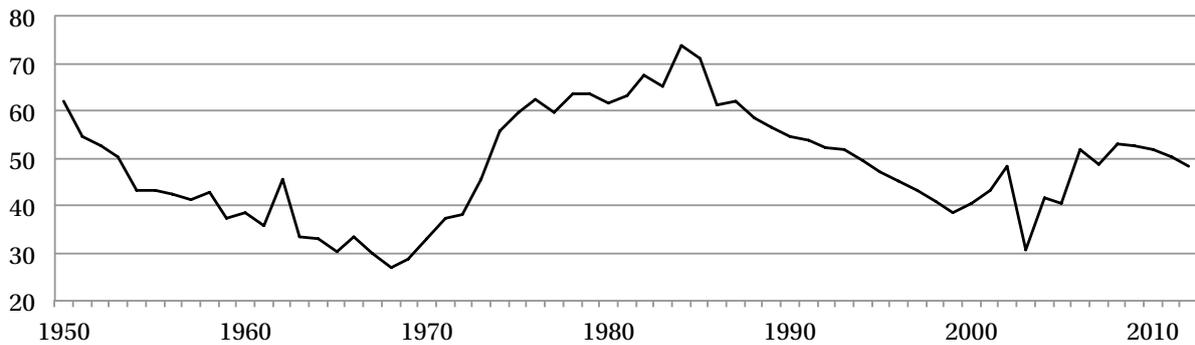


Figure 8: Coal Levelized Cost (\$2010/MWh)

There is thus a consensus around coal powered electricity: its levelized cost was around 50\$ of today per MWh over the last four decades and it is scheduled to stay at the same level, in the absence of a carbon price. Obviously, the crucial variable today is the cost of *carbon capture* since generators are increasingly under pressure to produce “carbon free” electricity. We may thus conclude that nuclear power in the US has been some 44% dearer than coal power and that the premium is likely to increase. Indeed, if the French estimates regarding future liabilities and cost of the novel EPR reactor are of any use, they tell us that the 75\$/MWh figure achieved by past US nuclear power is a lower bound for the future cost of that technology in the US.

We include a minimal comparison with natural gas, the successful fossil fuel for electricity generation over the last decades. The latest assessment by [EIA \(2013\)](#) uses an overnight cost of 0.9 \$/W, O&M of 23\$/kW per year, a 30 years lifetime and a 5% interest rate. Natural gas is a flexible source with limited carbon emission but not a baseload technology, hence its capacity factor is determined by market conditions. For this rough exercise, we choose 66% and find a levelized cost of 14 \$/MWh to which the fuel cost must be added. Given the central 50 \$/MWh hypothesis, we obtain a final levelized cost of 64 \$/MWh. Great care must be taken to handle this figure as it remains highly sensitive to fossil fuel prices (which vary by a factor three between the US and Japan for instance) and the variability of demand. We may nevertheless restate a folk theorem, natural gas powered electricity, without carbon pricing, is more flexible and cheaper than nuclear power in almost all possible market configurations.

6.4 Comparison with Wind Power

There is an intense debate regarding the optimal substitute to carbon emitting electricity sources. As shown with the life cycle analysis of [ExternE \(2002\)](#), nuclear power and wind power have low carbon content which makes them leading contenders to replace coal and natural gas in the coming decades. We are therefore warranted to pit wind against the atom in purely economic terms, neglecting other important dimensions such as scalability, intermittency, security of supply, environmental impact, social impact or nuclear proliferation.

Regarding wind power, the latest assessment by [EIA \(2013\)](#) uses an overnight cost of 2 \$/W, O&M of 40\$/kW per year, a 25 years lifetime and a 5% interest rate. [Boccard \(2009\)](#) has measured the long term capacity factor in the leading countries that have adopted this technology. This

index figure is influenced first of all by nature but also by the quality of sitting sites for wind farms. The updates for the US and Europe over the 2002-2011 decade are respectively 27.5% and 21.3%. We thus obtain a wind power levelized cost of 76\$/MWh for the US and 78 €/MWh for Europe.³⁴

In all likelihood, nuclear power will be more expensive than wind power in Europe since they are on par only in the best case for nuclear whereas the numbers for wind power are quite stable. The comparison between these two electricity generating technologies in the US is even clearer since the wind resource is better and the nuclear economics look worse once we account for future liabilities.

7 Policy Implications

Thanks to the cost information released by the [Court of Audit \(2012\)](#)'s report, we have been able to appraise the cost of the French nuclear power sector at about twice the previous estimate arrived at by [Grubler \(2010\)](#); this in itself proves the value of this novel piece of information. In hindsight, we understand why French governments were reluctant to share this information. Due to a difference in span, we also find a true cost well above the price set by the French government. Nuclear power thus appears dearer than professed by its zealous proponents essentially because operating expenses are high and the low capital cost only weights for a quarter of the total bill. At the same time, our exercise proves that nuclear power need not be ruinously expensive as has been the case in the US and the UK.³⁵ The French experience shows however that capital expenditure is only part of the story since O&M and future liabilities can easily overcome it, making nuclear expenses last for decades, a strong form of path dependence.

Extrapolating this localized information towards other countries is difficult. Based on the fact that both the US and French data show a high positive correlation between construction time and capital cost, we may treat the former which is publicly available for all stations around the world, as an acceptable proxy for the latter. According to this hypothesis, Japan, Korea, Taiwan and China who have managed to build nuclear power stations faster than France should also have done so at a moderate cost. Their positive experience (contrasted with worse ones in many places) confirms the need for the State to engage with its full political and financial weight and for the industry to be cohesive if not monopolistic. Yet, these countries have little experience with decommissioning or the management of the back-end cycle; they are also having issues with security of operation, to say the least, which in all likelihood will boost their cost in the near future.³⁶ A prudent assessment would therefore put these countries on par with

³⁴We use here the 2012 OECD PPP exchange rate at 1.25\$/€ rather than the French rate since we look at the wind resource over the entire continent.

³⁵[Jeffery \(1991\)](#) recalls how the British government discovered in 1989, while privatizing the electricity supply industry, that the true cost of nuclear power was twice greater than previously reported and possibly three times more expensive than coal power, thus forcing to keep all nuclear stations into publicly hands.

³⁶Fukushima will definitively increase the cost of nuclear power in Japan while the recent scandals regarding the use of fraudulent materials in Korean plants will probably lead to a reorganization of the industry and its regulation in the next decade. China is having the same difficulties as other countries in locating a nuclear fuel facility as it

France recalling that O&M is the area where they may outperform France's lackluster record.

Our findings may inform governments of advanced economies but it seems that their position is firmly set at the moment. In any case, the economics are only a secondary side of the overall nuclear equation for them. The developed asian countries (Japan, Korea, Taiwan) who actively pursue nuclear power are in a markedly different position. They have no fossil fuel resources, little high voltage connection with neighbors and occupy a small geographical area that makes the large scale development of renewables difficult and costly.³⁷ To guarantee their electricity supply, nuclear power is the only scalable baseload technology avoiding the vagaries of swinging fossil fuel prices (in the medium term).³⁸ This still leaves them at the mercy of disruptive events³⁹ which is why they will probably continue to support the nuclear option, trying to combine security with cost containment. The driver of nuclear power expansion in populous developing nations (China, India, Brazil, Mexico, Pakistan or South Africa) is similarly to keep up with the growth of electricity demand (which rises faster than economic growth).⁴⁰ This imperious motive thus overpowers cost considerations. Yet, apart from China, these countries have failed to build nuclear power stations efficiently since their construction times are about twice longer than the best in class. Given the inherently difficult long term management of large scale, capital intensive projects, one would advise against anything but buying turn-key nuclear power plants at a fixed price from experienced foreign makers.

To conclude, we may say that absent a carbon price, coal is cheaper than wind while our study has shown that current French nuclear stations produce electricity at a higher true total cost than wind power. It seems therefore that any kind of electricity with a low carbon content is bound to be expensive and shows no sign of becoming cheaper, that is unless a major scientific breakthrough is achieved in fusion or in a renewable field. At the same time, even nuclear power at 80 €/MWh remains quite affordable for the vast majority of advanced country citizens given the current retail price of about 200 €/MWh in Europe. The pros and cons of nuclear then revolve around its contribution to climate change mitigation and its negative long term impact on the environment.

Appendix A

A referee wondered whether the main source of information on which this article is based was trustworthy given the history of deception and secrecy surrounding the nuclear power industry. This appendix addresses this quandary by the affirmative.

meets unexpected popular resistance.

³⁷They lack outstanding wind and solar resources.

³⁸The technology still relies on a non domestic fuel, uranium, and foreign patents but all come from allies (US, Canada, Australia); it also allows a stable long term planning.

³⁹After Fukushima, all Japanese nuclear plants were stopped for security evaluation and upgrading, forcing the population to drastically reduce its electricity use in order to avoid blackouts. Likewise, Korea may see some [rolling blackouts](#) during the coming year because several reactors had to be stopped after the discovery of some forged safety certificates. Summer blackouts were only avoided thanks to via a nationwide energy-saving campaign

⁴⁰ As their populous middle classes start to enjoy the quality of life the West has known for decades, electricity demand grows at an accelerated pace (cf. [Wolfram et al. \(2012\)](#)).

Opinion surveys have shown that a majority of the population is opposed to civil nuclear power, even when the government and the major parties are in favor, such as in France. Unsurprisingly, the opposition is strongest in countries without such an industry. As recalled by Brouard et al. (2012) and displayed on Figure 9, exceptional periods aside, French opinion has been slightly antinuclear over the past decades.⁴¹ Yet, the French nuclear power industry has long been excluded from politicization. Between 1958 and 1988, a broad consensus exists whereby all parties heavily support nuclear development; at the same time, the government refrains from any serious communication (much like other countries with a nuclear power sector).

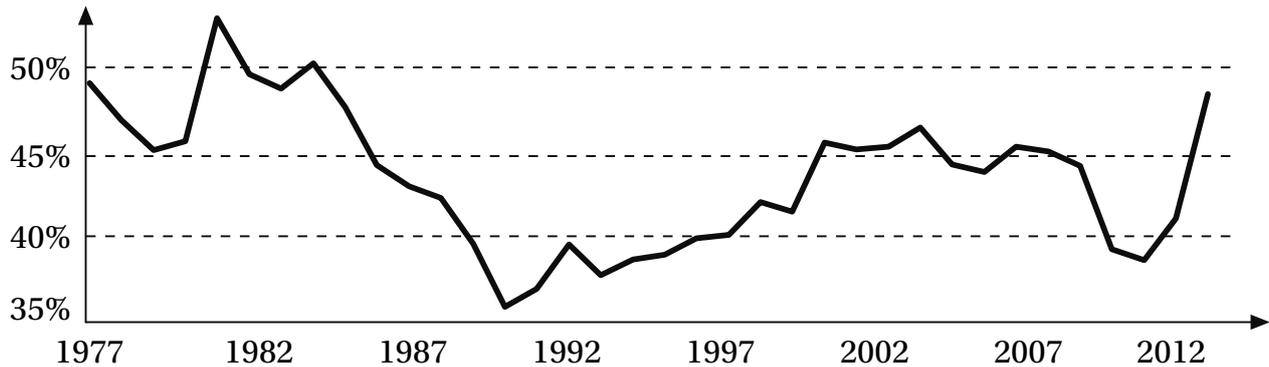


Figure 9: Mood favorable to Nuclear Power in France (%)

During in the 1990s, the fall to insignificance of the pro-nuclear communists and the rise of the anti-nuclear greens forces the socialist party to modify its position accordingly, in order to secure a majority in parliament whenever it wins elections (without achieving majority). The support for the industry has never waned but the socialist party has agreed to limit the growth of nuclear power and to more stringent security. Even conservatives have followed the opinion's mood (and European peer pressure) by passing a transparency law and creating the nuclear security agency in 2006. From a maximum support in 2004 over a two decades period, nuclear support has constantly decreased until March 2011 reaching a two decades low point when the Fukushima accident takes place. The greater level of European integration achieved by now means that the response takes an European nature, unlike in 1986 at the time of the Chernobyl catastrophe. European governments order stress tests of their nuclear installations to be run in coordinated fashion by national nuclear security agencies.

In France, the conservative government as well as their supporting media consider the event as extremely serious and even doubt the veracity of the official Japanese communiqués, as if they wanted to show off the inherent security of the French nuclear industry. There is here a radical change of attitude for the French government with respect to its 1986 treatment of Chernobyl which triggered a long controversy regarding whether or not it lied to the nation. It is against this background that the green party lashes out against nuclear energy during the development of the Fukushima accident. The conservative president is then forced to agree to something all of his predecessors successfully battled, an independent economic [audit](#) of the nuclear power

⁴¹This longitudinal measure uses Stimson's [mood](#) technique across two hundreds heterogeneous opinion surveys.

sector by the *Cour des Comptes*.

This independence of this revered institution is recognized by parties and NGOs alike (with the exception of the far-right "Front National" party).⁴² Over the last two decades it has become increasingly harsh with governments of all shades regarding their wasteful management of public monies. Neither in [March 2011](#), nor in [January 2012](#), when the report is published, do the pro-environment NGOs criticize the independence of the auditors, rather they herald a victory for transparency. We thus feel warranted to trust [Court of Audit \(2012\)](#) as a fully legitimate source of information to conduct a scientific investigation.

Attentive readers will note the surge in nuclear support starting precisely around the Fukushima accident. The explanation is political. With a view to the presidential election of May 2012, the conservative party takes advantage of the kerfuffle on the left regarding the future of nuclear power in France to politicize the issue by standing as the champion of a crucial sector for jobs, innovation, low electricity price and energy independence. Surprisingly, the level of adherence to nuclear in the public opinion rose to its highest level in 30 years. The June 2013 IFOP poll using the question already asked in 2011 and 2012 reveals only a slight decrease from the 2012 level.

Appendix B

The auditors reveal that EDF followed a smoothing policy to avoid excess capacity whereby it deliberately deferred the commercialization (aka industrial commissioning) of several units. We thus used the PRIS database to compute for each unit i the time between first grid connection (aka first coupling b_i) and the start of commercial operation (c_i) as a percentage of the time needed to reach grid connection since the start of construction (a_i) i.e., $x_i = \frac{c_i - b_i}{b_i - a_i}$. [Figure 10](#) displays this index for all reactors ordered by construction start. Six outliers shown in red are clearly identified. Their values are fitted in blue and the corrected commercialization dates are subsequently used in this paper.

For the 54 Westinghouse reactors, $c_i - b_i$ has a seven months mean and a coefficient of variation of about one month. Likewise, in the US, this measure has a five months mean and a coefficient of variation lesser than two months.

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⁴²The guarantee of neutrality rests on the collegiality in the formulation of findings and recommendations thereby avoiding partial and subjective views to college official. In practice, it means that the college includes members affiliated with all the main parties in power.

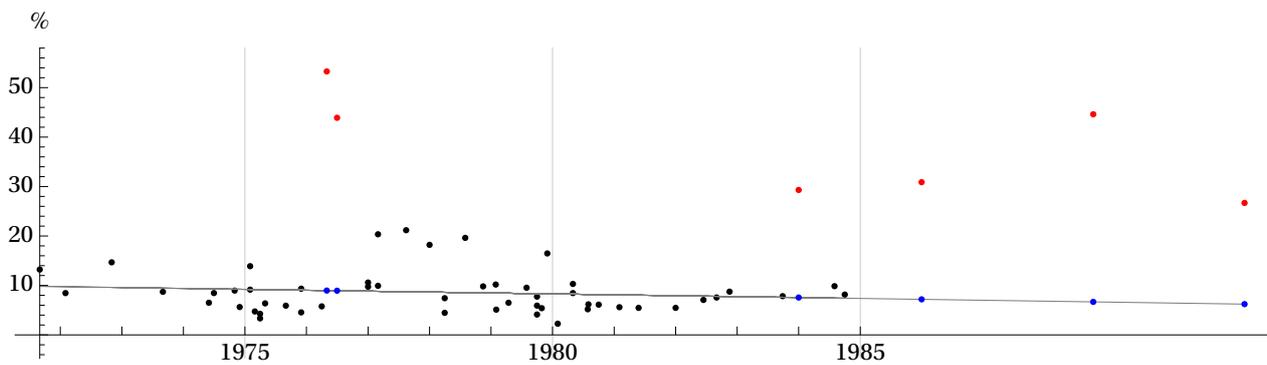


Figure 10: EDF Smoothing Policy regarding Commercialization

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