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**Revisiting the cost escalation
curse of nuclear power
New lessons from the French
experience**

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REVISITING THE COST ESCALATION CURSE OF NUCLEAR POWER. NEW LESSONS FROM THE FRENCH EXPERIENCE

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Abstract

Since the first wave of nuclear reactors in 1970 to the construction of Generation III+ reactors in Finland and France in 2005 and 2007 respectively, nuclear power seems to be doomed to a cost escalation curse. In this paper we reexamine this issue for the French nuclear power fleet. Using the construction costs from the *Cour des Comptes* report, that was publicly available in 2012, we found that previous studies overestimated the cost escalation. Although, it is undeniable that the scale-up ended up in more costly reactors, we found evidence of a learning curve within the same size and type of reactors. This result confirms that standardization is a good direction to look, in order to overcome the cost escalation curse.

Keywords: French nuclear power, construction cost, learning effects

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1 Introduction

The cost escalation that has characterized the construction of new nuclear power plants seems to put into question the economic viability of this technology as part of the energy mix in different countries.

In the case of the U.S, where 104 nuclear reactors have been installed, the overnight cost in USD₂₀₁₀/MW for the first unit was 7 times less than the one for the last reactor. This phenomenon has been widely studied in economic literature¹, and the general understanding is that the decentralized and heterogeneous way in which the nuclear fleet grew and the stricter safety rules that the Nuclear Regulatory Commission set after Three Mile Island accident² are the main drivers of the U.S cost escalation.

In turn, France has the second largest nuclear fleet worldwide (58 reactors) and its nuclear program has been catalogued as a success. According to David and Rothwell (1996), the centralized and monolithic industrial structure has been the key element in avoiding the U.S cost escalation path. Likewise, Grubler (2010) argued that due to this centralized institutional setting, the nuclear fleet in France grew rapidly, substantially and systemically.

However, when the French construction cost were analyzed by Grubler (2010), he found an important cost escalation. The comparison between the construction costs in FF₉₈/kW for the units installed in 1974 and the post 1990 constructed reactors, yielded in an increase by a factor of about 3.5. This finding suggested that even under the best conditions as prevailing in France (i.e. centralized decision making, high degree of standardization and regulatory stability), cost escalation is inherent to nuclear power.

Nowadays, history is repeating itself. The cost escalation is confirmed with the construction of the first Generation III+ reactors. In Finland, the original fixed-price contract for the Olkiluto EPR³ was for €3 billion in 2003, which meant a cost prevision of €₂₀₁₀ 2.100/kW. In 2010, the costs were revised and it was acknowledged that they had reached €₂₀₁₀ 5.7 billion (i.e. €₂₀₁₀ 3.500/kW⁴).

¹ See Komanoff (1981), Zimmerman (1982), Cantor and Hewlett (1988), McCabe (1996) and Cooper (2012),

² See Cantor and Hewlett (1988) and Cooper (2012)

³ European Pressurized Reactor

⁴ <http://www.nirs.org/reactorwatch/newreactors/eprcrisis31110.pdf>

Similarly, the initial cost of the Flamanville EPR reactor in France increased from to €₂₀₁₀ 3.3 billions to €₂₀₁₁ 6 billions, with an expected delay of 9 years⁵. These construction costs represent €₂₀₁₀ 3.650/kW, that is to say, almost three times the €₂₀₁₀ 1.250/kW of the last N4 nuclear reactor built in France (Civaux).

For the Westinghouse AP1000 the story is the same. According to Parsons and Du (2009), the overnight costs registered in the applications submitted to the Nuclear Regulatory Commission lie between USD₂₀₁₀ 3.650/kW and USD₂₀₁₀ 5.100/kW. This represent at least a 75% increase with respect to the USD₂₀₁₀2.400/kW estimated in 2003. More recently, Rosner and Goldberg (2011a) from the University of Chicago also updated their previous study and estimated an average cost for the AP1000 equal to USD₂₀₁₀ 4.210/kW.

In addition, we have seen an important decrease in the costs of competing energy technologies, which undermines even more nuclear power competitiveness. On the one hand, the prices of natural gas have decreased significantly due to the use of shale gas in the U.S; and on the other, renewables have registered important learning effects. For instance, Lindman and Söderholm (2012) found that the kW coming from wind farms decreases more than 10% every time that the installed capacity doubles.

On top of that, we may expect that Fukushima-Daiichi accident to have consequences in terms of cost. Safety authorities might impose stricter licensing rules and/or greater public opposition to installing new nuclear power plants could induce delays and therefore cost overruns.

So far, it seems that there is no escape from this curse. But before giving up, it is worth reviewing the French experience using the new data that is available. It is important to mention that Grubler made his cost assessment using estimations based on an annual investment report of *Électricité De France* (EDF) from 1972 to 1998. At the time of this publication, reliable data on the cost of the French nuclear program were not available.

Only until the beginning of 2012, the past construction and R&D expenses related to French nuclear power were publicly available, due to a request from the Prime Minister to the national audit agency *Cour des Comptes*. This report brought together all the data concerning the

⁵ http://www.lemonde.fr/planete/article/2011/11/10/sur-le-chantier-de-l-epr-a-flamanville-edf-est-a-la-moitie-du-chemin_1602181_3244.html

actual construction costs for the 58 reactors installed in France. Using this data, the cost escalation is less severe than what was argued.

In the light of this result, in this paper we reexamine the cost drivers for the French nuclear power program using the data of *Cour de Comptes* report. We investigate the existence of scale and learning effects, as well as the relation between safety performance and costs. We propose to use a principal component regression approach to deal with the multicollinearity among the main explanatory variables.

Our results suggest that neither the scale-up nor cumulative experience induced cost reductions, but we have found a positive learning effect within similar types of reactors. This finding supports the idea of standardization as a strategy to reduce the cost overruns linked with uncertainty in the construction of complex technologies. Additionally, we found that those reactors with better performance, in terms of safety, are related with higher costs; thus improvements in safety unsurprisingly, can also be considered as a driver of the cost escalation.

The rest of the paper is organized as follows. Section 2 describes the data and its sources, then sets out the model and estimation procedure. The results are presented in Section 4. Finally, Section 5 concludes.

2 Construction cost escalation: Data and Model

After the publication of the *Cour de Comptes* report, we studied the EDF investments for the second generation of reactors, that accounts the actual construction costs of the 58 commercial units currently operating⁶, to compare them with previous studies, estimate a cost function and investigate its main drivers.

Figure 1 compares the official data with the estimated costs computed by Grubler (2010). We can conclude that the figures for the first reactors are quite accurate but those for the latest ones were overestimated. This discrepancy means a difference of 5.21 between the annual average rate of growth using Grubler's costs estimations expressed in $\text{€}_{2010}/\text{kW}$, and the one using the *Cour de Comptes* construction costs. For the former, we found an average annual increase equal to 8.97% and for the latter, we got an increase of 3.76% on average per year.

⁶ See Appendix A

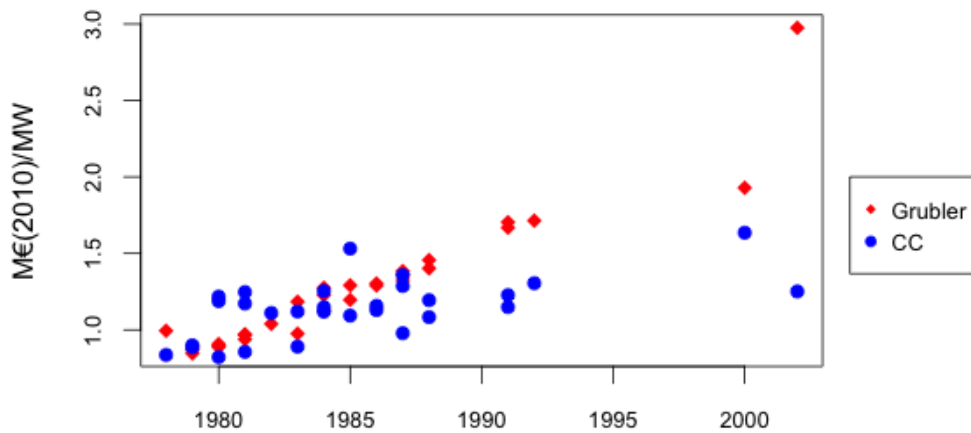


Figure 1: Grubler vs Cour de Comptes construction costs

As mentioned before, technological heterogeneity is viewed as one of the main explanations for the cost escalation in the U.S Two types of technologies (Pressurized Water Reactor and Boiling water reactor) have been installed and practically all of the units have customized sizes and designs. In contrast, the French nuclear fleet is considered to have a high degree of standardization, characterized by three different *paliers*. This categorization collects reactors by size. The first one comprises 34 installed reactors, all of them have 900MW nameplate capacity. The second *palier* includes 20 reactors with 1300 MW and the last one contains 4 reactors with 1450 MW of installed capacity.

On top of that, within each *palier* it is possible to find different types of reactors. The first *palier* has 3 types of reactors CP0, CP1 and CP2. Although all of them have the same capacity, they differ in the conception of their intermediary cooling systems. In the second *palier*, there are two types of reactors P4 and P'4 which differ in the layout of the structure that contains the fuel rods and the circuitry. Finally, in the last *palier* there is only one type of reactor, called N4. This design not only differs in capacity with the rest of reactors, but also in the conception of the steam generators, primary pumps and command room⁷.

Figure 2 shows the construction cost in $\text{€}_{2010}/\text{MW}$ for the French nuclear plants per type of reactor. It is clear that the cost escalation in France is also related to changes in the installed technologies. The

⁷ For a detailed description of the differences between the *paliers* and types, see http://rapport-annuel2010.asn.fr/fichiers/Chap_12_2010.pdf

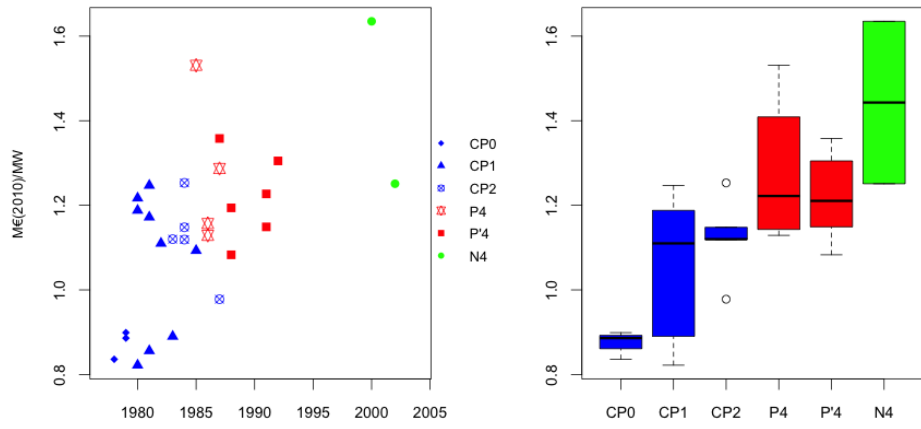


Figure 2: Cour de Comptes construction cost by Palier and Type

average cost for the first series of reactors (CP0) was the smallest, and it continuously increased as other types were installed. In this sense, Grubler (2010) stated that the high cost escalation towards the end of the program is precisely the result of the "gradual erosion of EDF determination to standardize".

By using a linear regression model, we seek to determine the construction cost main drivers. We assume a Cobb-Douglas cost function in which the explanatory variables are: capacity, experience, safety performance indicators and finally a random error.

$$\ln(C_i) = \beta_0 + \beta_1 \ln(Cap_i) + \beta_2 EXPI_i + \beta_3 EXPP_i + \beta_4 EXPT_i + \beta_5 UCL_i + \beta_6 US7_i + \beta_7 \ln(LTime_i) + u_i \quad (1)$$

Where:

- C_i : Construction cost for the pair of units i in €₂₀₁₀ per MW
- Cap_i : Installed capacity in MW
- $LTime_i$: Construction leadtime in months
- $EXPI_i$: Number of completed reactors at the time of the construction of plant i

- $EXPP_i$: Number of completed reactors within the same palier at the time of the construction of plant i
- $EXPT_i$: Number of completed reactors within the same type at the time of the construction of plant i
- UCL_i : Lifetime average Unplanned Capability Loss Factor for unit i
- $US7_i$: Lifetime average Unplanned Automatic Scram for unit i

Regarding capacity, in the U.S case the evidence against scale effects is conclusive. Zimmerman (1982), Krautmann and Solow (1988), Cantor and Hewlett (1988) and McCabe (1996) found that the construction of larger reactors⁸ increased the cost per MW installed. According to Cantor and Hewlett (1988), bigger units increase project complexity, subjecting them to managerial problems and stricter regulatory scrutiny. The positive correlation of lead time and size thus result in higher costs per MW.

On the contrary, the effect of the overall experience variable in construction costs is diverse. Komanoff (1981) and Zimmerman (1982) found positive evidence of a learning curve. They however recognized that the multicollinearity between the time trend and industry-cumulated experience, might bias their estimates.

This issue was solved by introducing the experience at firm level (constructor) and dummy variables to differentiate the management regime (utility or outsider). The learning effects were significant only when utilities constructed the plant⁹.

Given that EDF has been the only builder and utility, it is not possible to distinguish between industry and firm experience or to include dummies for management regimes. Nevertheless, we can distinguish experience within *paliers* and types of reactors. Therefore, to test the presence of learning effects, we considered three variables. The first took into account the overall experience ($EXPI$), the second variable only

⁸ Except by Komanoff (1981) pioneering study that suggested a cost decline by 13% when doubling reactor's size; nevertheless subsequent papers rejected this result.

⁹ This striking result was addressed later by Cantor and Hewlett (1988) and McCabe (1996). The former suggested that the market power of experienced firms allow them to charge higher prices, so the learning effects are kept as savings, whereas the latter found that what explains this difference are the poor incentives of the cost-plus contracts under which nuclear plants were procured to external constructors.

added the previous reactors made within the same *palier* (*EXPP*) and the last one accounted the reactors of the same type (*EXPT*).

Besides of scale and learning effects, one could also be interested in identifying whether the cost escalation is linked with safety improvements. According to Cooper (2012), safety variables (fines and the number of safety standards and rules adopted by the NRC) are the most consistent predictors to explain the cost escalation in the U.S. In previous studies (Komanoff (1981), Zimmerman (1982), Cantor and Hewlett (1988), McCabe (1996)), safety improvements were related with the stringency of the regulatory agency which was represented with a time trend always found to be significant and positive.

For the French case it is hard to measure regulatory activity. The *Autorité de Sûreté Nucléaire* (independent regulatory agency) was created in 2006, 4 years after the last reactor was built in 2002. Additionally, Grubler (2010) found that there was no regulatory documented incidence from 1970 to 1999. However, Finon (2012) recognized that despite the stability in the French safety rules, EDF integrated safety reinforcements gradually into new reactors.

To test if safety improvements are related to construction costs, we included in the model two safety performance indicators defined by The World Association of Nuclear Operators (WANO) and adopted by the International Atomic Energy Agency (IAEA).

The first one is *Unplanned Capability Loss Factor* (UCL_i), which reflects a reactor's ability to maintain the reliability of systems and components. This indicator belongs to the first category of the safety performance indicators used by the IAEA, that seeks to quantify how smoothly the plant operates. The *UCL* indicator shows the percentage of energy that the plant was not capable of supplying due to deviations from normal operations.

The second indicator is *Unplanned Automatic Scram* ($US7_i$), which belongs to the second category defined by the IAEA. Within this group, all the indicators quantify if the plant operates at low risk. The *US7* tracks number of automatic shutdowns during one year (7.000 hours) of operation. We have chosen this measure because it gives a direct indication of the frequency of actual challenges to the systems, that submit plant equipment to extreme thermal loads and increase the risk of serious accidents.

In addition to the *Cour de Comptes* data, we have also gathered data

from the Power Reactor Information System (PRIS) database published by the IAEA. We have taken the installed capacity in MW, the year in which the reactor was constructed, the construction period length (in months), the number of reactors that were built by EDF previously to account the experience, and the average lifetime UCL and US7 for each pair of units. Descriptive statistics of the data are presented in Table 1.

Table 1: Descriptive statistics

Variable	Unit	Mean	Median	Minimum	Maximum	Std
Ln Cost	Ln(€ ₂₀₁₀ /MW)	0.119	0.138	-0.196	0.491	0.170
Ln Cap	Ln(MW)	7.656	7.517	7.461	7.987	0.196
EXPI	# reactors	27.413	26	1	56	17.307
EXPP	# reactors	12.034	12	1	30	8.974
EXPT	# reactors	5.103	4	1	16	4.169
UCL	%	7.127	7.075	3.075	11.959	2.083
US7	events/7000 hours critical	0.773	0.690	0.180	1.40	0.3169
LTime	Ln(months)	151.931	143	115	288	37.183

2.1 Multicollinearity and Principal Component approach

One of the main problems identified in the literature of nuclear construction cost escalation is the multicollinearity between explanatory variables included in the cost function, in particular the high correlation between installed capacity, industry experience and leadtimes.

To deal with this problem, Zimmerman (1982) suggested to use a monotonic transformation of overall experience instead of the original variable. In subsequent studies, such as those of Cantor and Hewlett (1988) and McCabe (1996), the issue was solved by taking the builder's experience into account instead of the overall industry experience, which eased the high correlation among these variables.

For the French case the multicollinearity problem is severe. There is a single builder (EDF), the scale-up was progressive and bigger reactors experienced greater leadtimes. As we can observe in Table 2, these three variables (Capacity, Overall experience and leadtime) are highly correlated, which warns the difficulty of obtaining significant results in a linear regression framework.

Table 2: Correlation Matrix

	Ln Cap	EXPI	EXPP	EXPT	Ln Ltime	US7
Ln Cap	1	0.87	-0.45	-0.24	0.82	-0.08
EXPI	0.87	1	0.03	-0.02	0.77	-0.23
EXPP	-0.45	0.03	1	0.55	-0.32	-0.29
EXPT	-0.24	-0.02	0.55	1	-0.23	-0.22
Ln LTime	0.82	0.77	-0.32	-0.23	1	-0.23
US7	-0.08	-0.23	-0.29	-0.22	-0.23	1

Indeed, when we include all of them in a linear regression, the coefficients are imprecisely estimated (See Table 3). On top of that, we find high estimates for the Variance Inflation Factor (VIF), which confirms that the multicollinearity problem is severe.

Table 3: Linear regression estimates

Coefficients	Estimate	Std. Error	t value	$Pr(> t)$
(Intercept)	7.700	10.034	0.767	0.451
Ln Cap	-0.252	1.216	-0.208	0.838
EXPI	0.017	0.014	1.206	0.241
EXPP	-0.002	0.015	-0.186	0.854
EXPT	-0.006	0.008	-0.743	0.465
Ln LTime	0.261	0.344	0.761	0.455
UCL	-1.410	0.882	-1.598	0.125
US7	-0.009	0.018	-0.487	0.632

Table 4: VIF for explanatory variables

Ln Cap	EXPI	EXPP	EXPT	Ln LTime	UCL	US7
87.808	93.856	29.501	2.143	8.257	24.520	2.328

The traditional way of solving multicollinearity problems is to eliminate one or more explanatory variables. We have tried different specifications. Nevertheless they did not result in significant estimates and the VIF remained high. The results of these models are shown in Appendix B.

Unfortunately, within this framework it is not possible to figure out the main drivers, because our data set appears redundant. By using a

principal component regression, we overcame this limitation. With this method we can obtain relevant information from our data set, reducing it to a lower dimension and making it possible to reveal simplified underlying correlations between the costs and the explanatory variables.

Principal component analysis is an ancient multivariate technique developed by Pearson (1901) and Hotelling (1933). In economics this method has been applied in a wide range of subjects¹⁰, for instance, in macroeconomics and finance (Fifield and Sinclair, 2002), development (Zanella and Mixon, 2000) and socio-economic indexes (Filmer and Pritchett, 2001).

The main idea of this procedure is to take the correlation matrix, that we are going to denote by $\mathbf{C} = \mathbf{X}'\mathbf{X}$ (where \mathbf{X} is the $n \times k$ matrix of centered and scaled explanatory variables) and compute the $k \times k$ eigenvector matrix¹¹ \mathbf{V} .

Given that $\mathbf{V}\mathbf{V}' = \mathbf{I}$, we can rewrite a lineal model $Y = X'\beta^*$ as follows.

$$Y = \beta_0^* \mathbf{1} + \mathbf{X}\mathbf{V}\mathbf{V}'\beta^* \quad (2)$$

$$Y = \beta_0^* \mathbf{1} + \mathbf{Z}\alpha \quad (3)$$

Where \mathbf{Z} is the $n \times k$ matrix of principal components. This matrix contains the same information that \mathbf{X} but the columns are arranged according their share in the variance. Each principal component is a linear combination of the explanatory variables. The weights are defined by the characteristic vectors or loadings (matrix \mathbf{V}) and the roots (eigenvalues), denoted by λ , identify the most important components (the higher the eigenvalue, the higher the share in the variance).

Once this decomposition is done, the next step in this framework is to eliminate the principal components (columns of Z) associated with the smallest eigenvalues (λ) in order to reduce the variance that is causing the multicollinearity and be able to estimate significant coefficients.

¹⁰We do not pretend to give a comprehensive list of principal component analysis in economics, rather to mention some examples.

¹¹Recall that the eigenvectors of a square matrix \mathbf{A} are defined as the vectors that solve $\mathbf{A}\mathbf{W} = \lambda\mathbf{W}$, where λ is a real or complex number called eigenvalue. They can equivalently be defined as the vectors that solve $(\mathbf{A} - \lambda\mathbf{I})\mathbf{W} = \mathbf{0}$

3 Results

The characteristic vectors and roots for the correlation matrix of the model¹² are presented in Table 5.

Table 5: Eigenvectors and eigenvalues of Model 1

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6	Comp 7
Ln Cap	0.563		0.180		-0.211	-0.410	0.651
EXPI	0.522	0.172	0.299	0.338	-0.144	-0.220	-0.652
EXPP	-0.219	0.493	0.228	0.702		0.157	0.374
EXPT	-0.162	0.473	0.482	-0.564	-0.409	0.174	
Ln LTime	0.556				0.211	0.794	
UCL		-0.558		0.249	-0.716	0.312	
US7	-0.134	-0.430	0.765		0.459		
λ	81.309	66.434	20.658	13.796	10.206	3.464	0.131

This decomposition can be interpreted as follows. The first component is the most important because it explains the highest share of variance and, the variables with the highest loadings are those that explain the major trend in the data. The subsequent components show the correlations within variables, independent of previous components.

In our case, the first component explains 41% of the total variance and has high loadings from: capacity, cumulative experience and leadtime. This component represents what Cooper (2010) denominated as the *Bupp-Derian-Komanoff-Taylor* hypothesis. This hypothesis states that as nuclear power industry (vendors and utilities) gained experience, bigger reactors were made and this technological scaling-up induced greater complexity which resulted in longer leadtimes.

The second component accounts for 33% of the variance. The variables with high loadings are experience within *palier* and type and the two safety performance indicators. Given that in this component the loadings have opposite signs, constructing similar reactors (either in size or type), made improvements possible in terms of safety indicators in the latest units.

If we check the scores¹³ we can compare the reactors within each

¹²We have also consider a model without the variable of experience at the *palier* level ($EXPP_i$). The results are shown in Appendix C

¹³The scores represent the linear combination of the explanatory variables in each principal component for each observation

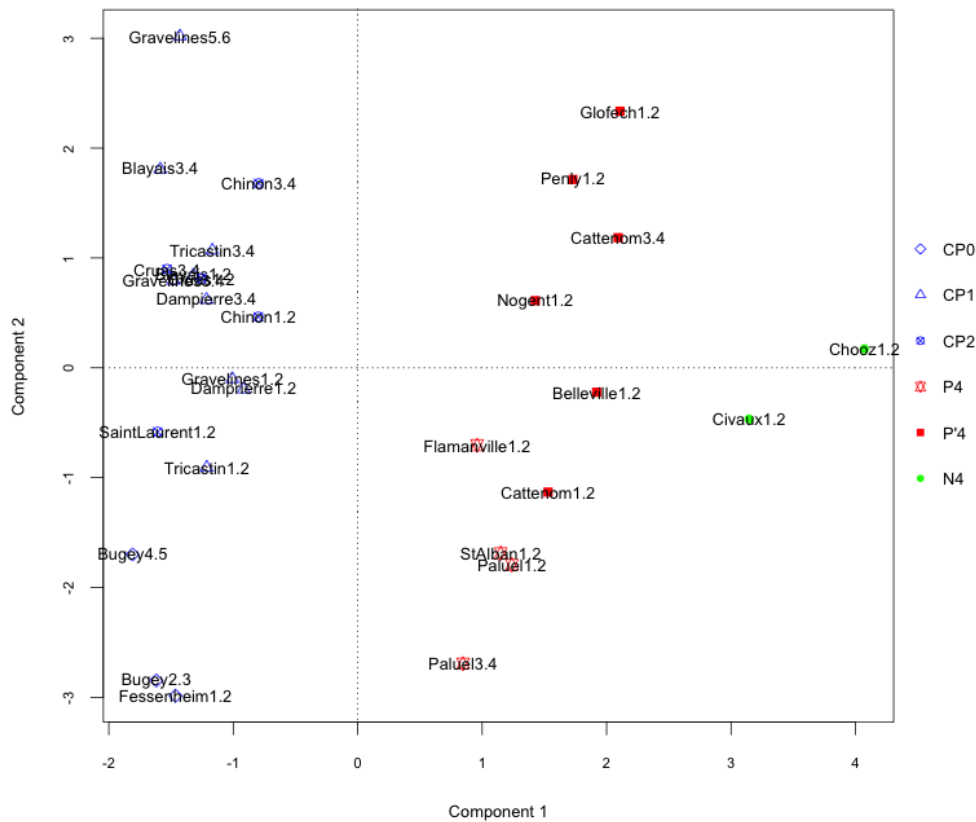


Figure 3: Scores of the first two components

component. In Figure 3, the scores for the first component are plotted on the horizontal axis. We can clearly see that they are clustered at the *palier* level, this result simply confirms the fact that bigger reactors were built as the industry gained experience but it took more time to construct them.

The second component is plotted on the vertical axis of the same Figure. Remember that this component represent the negative correlation between experience (in similar reactors) and safety performance. We can see that within each type, the units with higher scores are the latest in their series (more experience and better performance). For instance, Gravelines 5.6 and Blayais 3.4, correspond to the latest CP1 reactors. It is also the case for the P4 and P'4 series, where the reactors at Flamanville, Golfech and Penly were built after those installed at the Saint Alban, Cattenom and Belleville sites, respectively. For the same reason,

it is no surprise that reactors such as Fessenheim, Dampierre and Cattenom have small scores in this component, given that they can be seen as prototypes in their respective series.

To select the number of components to be included in the estimation, we chose the root mean squared error of prediction (RMSEP) criterion. Using the leave-one-out cross-validation method, we found that the RMSEP is minimized with the first two components.

Once the number of principal components had been selected, we computed the coefficients for the original linear regression. In Table 6 we present the estimates for our explanatory variables¹⁴.

Table 6: Principal Component Regression Results

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value	p-value	
Ln Cap	0.206	1.050	(0.280)	3.747	1.11e-03	***
EXPI	0.209	0.012	(0.002)	4.084	4.90e-04	***
EXPP	-0.046	-0.005	(0.002)	-2.177	4.04e-02	*
EXPT	-0.026	-0.006	(0.002)	-2.706	1.28e-02	*
Ln LTime	0.212	0.995	(0.255)	3.898	7.72e-04	***
UCL	-0.075	-0.036	(0.004)	-8.199	3.91e-08	***
US7	-0.081	-0.257	(0.041)	-6.215	2.95e-06	***

In the light of these results, we confirm that as in the U.S case, the scaling-up of the French nuclear program did not translate in cost reduction. This is a well known phenomenon in nuclear power, since the construction of larger reactors is more complex, hence such a project implies greater risk of cost overruns (Cooper (2010)). The principal component approach shows that the strong correlation among capacity, overall experience and leadtime represents the main driver to explain the cost escalation. Table 6 shows that an increase in the installed capacity will induce higher construction cost per MW.

Regarding overall learning effects, we also found that cumulated experience had not induced a reduction in costs. This result is often seen as a consequence of the intrinsic characteristics of nuclear power, i.e. lumpy investments and site-specific design (Cooper (2010), Grubler (2010)).

¹⁴Given that we have had to standardized our explanatory variables, we differentiate the coefficients for the centered and scaled matrix with $\hat{\beta}^*$ and we use $\hat{\beta}$ for the original data.

As mentioned before, Cooper (2010) suggests that with the construction of a new reactor, the experience gained by vendors and operators translates in adjustments and improvements, that complexify the reactors and make the new designs more expensive than their predecessors. In the French case, Grubler (2010) and Finon (2012) argue that the potential learning effects from the overall industry experience were not fully exploited, precisely because as they gained experience, it was decided to construct an entirely new French nuclear reactor.

Nevertheless, when we take into account the experience within the same *palier* and type, we find a positive learning effect. In Table 6, we can see that the estimates for these variables are negative, however their effect was less significant than the other variables.

The intuition behind learning effects within type of reactor is straightforward, but is less clear at the *palier* level, precisely because the reactors within them are not the same. A possible justification is that, each *palier* represents also a phase of the French nuclear program. Hence, the reactors within them were conceived and built during the same time window, which suggests that suppliers, workers and engineers did not change substantially during the construction of one *palier*, but they might have changed between them.

The negative sign in the experience variables means that some cost reductions were achieved due to standardization. Building similar reactors reduced the technological uncertainty linked with the adoption of a new design. This result can thus be seen as one of the potential sources of savings for future nuclear reactors, as well as one of the key differences between the U.S and France cost escalation drivers.

An other important result shown in Table 6, is that reactors with better safety indicators (UCL and US7) are related with higher costs. Therefore, we have some evidence that the latest reactors, although more expensive, have also embodied safety improvements.

4 Conclusion

In this paper, we sought to use the *Cour de Comptes* report to identify the main drivers of the construction cost escalation in France.

It was originally believed that the cost escalation was about a factor of 3.5, when comparing the unit costs from the units built in 1974 and those

finished after 1990 (Grubler (2010)). Using the new data, we found that the escalation was about a factor of 1.5 between the first and the last unit, thus the escalation was less severe and by no means comparable with the U.S case. Therefore, important lessons can be drawn from this program in order to identify the elements that should be taken into account to overcome or at least mitigate the cost escalation phenomenon.

On the basis of the analysis using the *Cour des Comptes* data, there is every reason to believe that the construction cost escalation is mainly due to the scaling-up strategy. It induced greater complexity and leadtimes which in turn meant an increase in costs per MW. As mentioned before, the absence of scale economies in nuclear power is not a new result, and with the construction of new Generation III and III+ reactors it is confirmed that larger reactors are more expensive. Hence, capacity could be one of the starting points in rethinking nuclear power strategy.

In this sense, several authors as Kessides (2012) and Rosner and Goldberg (2011*b*) have outlined the advantages of installing small modular reactors. They argued that these reactors have shorter construction schedules and lower market risk which reduces the cost of capital. Additionally, they considered that other cost savings can be achieved through off-site modules fabrication, as well as the learning by doing after the production of multiple modules.

This is in line with our results about learning effects. We found that overall experience did not traduce in lower costs but some gains were achieved due to the construction of same types of reactors. Given the nature of this result, it would appear likely that standardization is a strategy to overcome delays and uncertainties during the construction process and thus reduce the cost of the following reactors of the same series.

In view of the results regarding the safety indicators, it appears likely that reducing the risk of a serious accident has also played its part in the French cost escalation, as it was found by Cooper (2010) for the U.S case. Our model shows that in the conception of new nuclear reactors, safety improvements are undertaken (reflected in better safety indicators). In consequence when safety concerns are partly internalized in the construction costs, safer reactors are inherently more expensive.

For this reason, the economics of safety is perhaps the most challenging issue for the future of nuclear power. On the one hand, the terrible consequences of a nuclear disaster, such as the ones seen after Fukushima-Daiichi accident, leave no room for laxity. On the other

hand, the particular nature of serious nuclear accidents, huge damages but very low and uncertain probability of occurrence, makes it difficult to determine if the safety investments are cost-effective.

Once again, the French case teaches us an important lesson. Principal component analysis showed that the latest units of the same series have better performance in terms of the safety indicators used in the model. In this sense, standardization besides generating learning effects in the construction process, can also play a role in terms of achieving better safety levels.

Small reactors also seem to have some advantages in safety terms, given that as Kessides (2012) pointed out, a simpler design leads to a lower frequency of accident initiators and a lower core power density induce a more effective use of passive safety features, that are those system components that do not require operator control or electronic feedback in order to shut down safely in case of an emergency.

In summary, the cost escalation curse in nuclear power may have a solution. Taking into account the lessons from French nuclear program, a good strategy would be to limit the number of technologies to be installed in order to obtain learning effects not only in construction costs but also in operations, in particular in safety performance. It should also be considered that new technologies, as the small modular reactors, bring the possibility of reducing the scale of the units as well as off-site module fabrication, thereby reducing the complexity and leadtimes that have been consistently found to be the main drivers of the cost escalation phenomenon.

References

- Cantor, R. and Hewlett, J. (1988), 'The economics of nuclear power: Further evidence on learning, economics of scale and regulatory effects', *The Bell Journal of Economics* **13**, 297–310.
- Cooper, M. (2010), Policy challenges of nuclear reactor construction, cost escalation and crowding out alternatives. Unpublished manuscript.
- Cooper, M. (2012), Nuclear safety and nuclear economics. Unpublished manuscript.
- David, P. and Rothwell, G. (1996), 'Standardization, diversity and learning: Strategies for the coevolution if technology and industrial

- capacity', *International Journal of Industrial Organization* **14**, 181–201.
- Fifield, P. and Sinclair (2002), 'Macroeconomic factors and share returns: an analysis using emerging market data', *International Journal of Finance & Economics* **7**, 51–62.
- Filmer, D. and Pritchett, L. (2001), 'Estimating wealth effects without expenditure data or tears: An application to educational enrollments in states of india', *Demography* **38**, 115–132.
- Finon, D. (2012), L'économie du nucléaire revisitée. Unpublished manuscript.
- Grubler, A. (2010), 'The cost of the french nuclear scale-up: A case of negative learning by doing', *Energy Policy* **38**, 5174–5188.
- Hotelling, H. (1933), 'Analysis of a complex of statistical variables into principal components', *Journal of Educational Psychology* **24**, 417–441.
- Kessides, I. (2012), 'The future of the nuclear industry reconsidered: Risk, uncertainties and continued promise', *Energy Policy* **48**, 185–208.
- Komanoff, C. (1981), *Power Plant Cost Escalation Nuclear and Coal Cost, Regulation and Economics*, Van Nostrand Reinhold Publishing.
- Krautmann, A. and Solow, J. (1988), 'Economies of scale in nuclear power generation', *Southern Economic Journal* **55**, 70–85.
- Lindman, A. and Söderholm, P. (2012), 'Wind power learning rates: a conceptual review and meta-analysis', *Energy Economics* pp. 754–761.
- McCabe, M. (1996), 'Principals, agents and the learning curve: The case of steam-electric power plant design and construction', *The Journal of Industrial Economics* **XLIV**, 357–375.
- Parsons, J. and Du, Y. (2009), Update on the cost of nuclear power, Technical report, MIT.
- Pearson, K. (1901), 'On lines and planes of closest fit to systems of points in space', *Philosophical Magazine* **2**, 559–572.
- Rosner, R. and Goldberg, S. (2011a), Analysis of gw-scale overnight capital cost, Technical report, The University of Chicago.

- Rosner, R. and Goldberg, S. (2011*b*), Small modular reactors - key to future nuclear power generation in the u.s. Unpublished manuscript.
- Zanella, S. C. F. and Mixon, F. (2000), 'Is economic freedom one dimensional? a factor analysis of some common measures of economic freedom', *Journal of Economic Development* **25**, 17–40.
- Zimmerman, M. (1982), 'Learning effects and the commercialization of new technologies: The case of nuclear power', *The Bell Journal of Economics* **13**, 297–310.

Appendix A Cour de Comptes overnight construction cost

Pair of units	Capacity MW	Year	Type	Overnight Cost (M€2010/MW)
Palier 900 MW				
Fessenheim1.2	1780	1978	CP0	0,836
Bugey2.3	1840	1979	CP0	0,886
Bugey4.5	1800	1979	CP0	0,899
Dampierre1.2	1800	1980	CP1	1,217
Gravelines1.2	1840	1980	CP1	0,822
Tricastin1.2	1840	1980	CP1	1,188
Blayais1.2	1830	1982	CP1	1,110
Dampierre3.4	1800	1981	CP1	1,172
Gravelines3.4	1840	1981	CP1	0,856
Tricastin3.4	1840	1981	CP1	1,247
Blayais3.4	1820	1983	CP1	0,890
Gravelines5.6	1820	1985	CP1	1,093
SaintLaurent 1.2	1760	1983	CP2	1,120
Chinon 1.2	1740	1984	CP2	1,148
Cruas1.2	1760	1984	CP2	1,119
Cruas3.4	1760	1984	CP2	1,253
Chinon3.4	1760	1987	CP2	0,978
Palier 1300 MW				
Paluel1.2	2580	1985	P4	1,531
Paluel3.4	2580	1986	P4	1,157
St Alban1.2	2600	1986	P4	1,129
Flamanville1.2	2580	1987	P4	1,287
Cattenom1.2	2565	1987	P'4	1,358
Belleville1.2	2620	1988	P'4	1,083
Cattenom3.4	2600	1991	P'4	1,149
Nogent1.2	2620	1988	P'4	1,194
Glofech1.2	2620	1992	P'4	1,305
Penly1.2	2660	1991	P'4	1,227
Palier 1450 MW				
Chooz1.2	2910	2000	N4	1,635
Civaux1.2	2945	2002	N4	1,251

Appendix B Linear regression models

We have estimated different linear regression models in order to deal with the multicollinearity problem among the explanatory variables. As possible solutions we have decided to replace capacity with dummy variables at the type or palier level. With these variables we are allowing that the changes in technology or scale translate in different intercepts. Given that we have a small sample, the introduction of a dummy variable for each type of reactor reduces substantially the degrees of freedom thus we still get non significant coefficients as we can observe in the following tables.

Table 7: Linear regression estimates with dummy for type of reactor

Coefficients	Estimate	Std. Error	t value	$Pr(> t)$	
(Intercept)	8.309	4.063	2.045	0.055	.
CP1	0.202	0.114	1.768	0.093	.
CP2	0.445	0.261	1.702	0.106	
N4	0.704	0.676	1.042	0.311	
P'4	0.618	0.509	1.215	0.240	
P4	0.672	0.410	1.637	0.119	
EXPI	0.005	0.010	0.519	0.610	
EXPT	0.005	0.014	0.357	0.725	
Ln LTime	0.564	0.321	1.757	0.095	.
UCL	-2.221	0.888	-2.501	0.022	*
US7	-0.014	0.020	-0.680	0.505	

Table 8: VIF for the explanatory variables

EXPI	EXPT	LnLTime	UCL	US7
8.006	2.721	3.068	5.697	1.934

We have also tried a model without leadtime and overall experience in the linear regression; given that we already know that they are highly correlated with capacity. However, we still find that the coefficients are imprecisely estimated.

Table 9: Linear regression estimates with dummy for palier

Coefficients	Estimate	Std. Error	t value	$Pr(> t)$
(Intercept)	6.014	3.947	1.524	0.142
Palier 2	0.016	0.157	0.104	0.918
Palier 3	-0.049	0.271	-0.181	0.857
EXPI	0.014	0.007	1.922	0.068
EXPT	-0.008	0.008	-0.983	0.336
Ln LTime	0.343	0.347	0.986	0.335
UCL	-1.524	0.895	-1.703	0.103
US7	-0.012	0.019	-0.629	0.535

Table 10: VIF for the explanatory variables

EXPI	EXPT	LnLTime	UCL	US7
5.219	1.345	2.920	5.051	1.569

Table 11: Linear regression estimates with dummy for type and no leadtime

Coefficients	Estimate	Std. Error	t value	$Pr(> t)$
(Intercept)	-0.127	0.078	-1.627	0.118
CP1	0.208	0.111	1.866	0.076
CP2	0.259	0.249	1.040	0.310
N4	0.502	0.604	0.832	0.415
P'4	0.349	0.468	0.746	0.464
P4	0.382	0.385	0.992	0.332
EXPI	-0.0002	0.0110	-0.020	0.984
EXPT	-0.003	0.0141	-0.217	0.830

Table 12: VIF for the explanatory variables

EXPI	EXPT
2.349	7.610

Table 13: Linear regression estimates with dummy for type and no leadtime

Coefficients	Estimate	Std. Error	t value	$Pr(> t)$	
(Intercept)	-1.550	1.495	-1.037	0.311	
CP1	0.203	0.095	2.120	0.046	*
CP2	0.242	0.096	2.501	0.020	*
N4	0.289	0.241	1.199	0.243	
P'4	0.236	0.144	1.640	0.116	
P4	0.312	0.119	2.615	0.016	*
EXPT	-0.003	0.007	-0.527	0.603	
Ln LTime	0.294	0.309	0.952	0.351	

Table 14: VIF for the explanatory variables

EXPT	LnLTime
1.201	2.68

Appendix C Principal component regression

In this Appendix, we show the results for different specifications for the construction cost function using the principal component regression.

In general, the results are the same. The first component have high loadings of capacity, overall experience and leadtime and it is the main driver of the cost escalation and the second represents the negative relation between experience within similar types of reactors and the safety performance indicators.

Nevertheless, when we remove the experience within *palier* or one of the safety variables, the criteria to select the number of principal components to keep in the estimation leads to select only the first one. Thus the share of the variance that we use to estimate is smaller; however the signs remain the same as well as the main conclusions.

In Table 15, we have the loadings and eigenvalues for the model without the variable that captures the experience at *palier* level, i.e $EXPP_i$.

As in the original model, the first component has high loading of capacity, overall experience and leadtime. Which confirms that the main

Table 15: Eigenvectors and eigenvalues of Model without $EXPP_i$

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6
Ln Cap	0.535	-0.238	0.168	-0.215		0.763
EXPI	0.556		0.221	-0.131	0.601	-0.512
EXPT		0.582	0.639	-0.421	-0.269	
Ln LTime	0.553	-0.107		0.207	-0.732	-0.321
UCL	-0.214	-0.606		-0.711	-0.173	-0.227
US7	-0.223	-0.475	0.716	0.460		
λ	79.649	51.575	20.022	10.208	4.372	2.171

driver of the cost escalation was the scale-up. The second component has high loadings from the experience constructing the same type of reactors and the safety indicators. The opposite signs support our previous result, that suggest that the latest units in each series have the best safety performances.

In this model we found that the number of components that minimize the RMSEP is one. The estimates for the standardized and original variables are presented in Table 16. We obtain the same insights that with the original model. We confirm the absence of scale effects and an overall learning curve but we have found positive learning effects when building the same type of reactors. The negative values for the estimates related to safety indicators coincide with those found in the complete model, thus reducing the events that may lead to accidents is related with higher costs.

Table 16: PC Results for model without $EXPP_i$

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value	p-value	
Ln Cap	0.207	1.0518	(0.266)	3.939	0.0006	***
EXPI	0.215	0.0124	(0.003)	3.939	0.0006	***
EXPT	-0.021	-0.005	(0.001)	-3.939	0.0006	***
Ln LTime	0.214	1.003	(0.010)	-3.939	0.0006	***
UCL	-0.083	-0.083	(0.069)	-3.939	0.0006	***
US7	-0.086	-0.086	(0.254)	3.939	0.0006	***

We also have consider a model with only $US7$ as safety variable and other using UCL solely. The unique difference between these models is that in the number of components that minimize the RSMSE. In the first

one, with one component the criterion is minimized, in the second one is two.

Table 17: Eigenvectors and eigenvalues of Model without *UCL*

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6
LnCap	-0.568		0.173	-0.134	0.453	0.651
EXPI	-0.505	0.301	0.265	0.284	0.280	-0.652
EXPP	0.263	0.576	0.173	0.648		0.375
EXPT	0.205	0.543	0.454	-0.671		
US7		-0.521	0.814	0.172	-0.163	
Time	-0.549	0.103			-0.823	
λ	81.020	48.474	20.52	13.415	4.431	0.131

Table 18: PC Results for model without *UCL*

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value	p-value	
Ln Cap	0.208	1.060	(0.254)	4.165	4.03e-04	***
EXPT	0.185	0.010	(0.002)	4.165	4.03e-04	***
EXPP	-0.096	-0.010	(0.002)	-4.165	4.03e-04	***
EXPI	-0.075	-0.0181	(0.004)	-4.165	4.03e-04	***
Ln LTime	0.201	0.945	(0.227)	4.165	4.03e-04	***
US7	-0.034	-0.108	(0.025)	-4.165	-4.03e-04	***

We found similar results for the other safety indicator.

Table 19: Eigenvectors and eigenvalues of Model without *US7*

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6
Ln Cap	0.571		-0.101	-0.266	0.406	-0.654
EXPI	0.501	0.296	0.329	-0.279	0.223	0.652
EXPP	-0.276	0.510	0.698	-0.124	-0.155	-0.371
EXPT	-0.215	0.521	-0.581	-0.558	-0.177	
UCL		-0.602	0.231	-0.690	-0.327	
LnLTime	0.547	0.132		0.221	-0.789	
λ	80.616	57.097	13.797	12.874	3.473	0.140

Table 20: PC Results for model without *US7*

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value	p-value	
Ln Cap	0.213	1.085	(0.257)	4.217	3.549e-04	***
EXPT	0.227	0.013	(0.002)	5.103	4.097e-05	***
EXPP	-0.0267	-0.002	(0.001)	-1.808	8.427e-02	.
EXPI	-0.002	-0.001	(0.003)	1.803	8.504e-02	.
Ln LTime	0.220	1.0301	(0.227)	4.525	1.670e-04	***
UCL	-0.097	-0.046	(0.001)	-45.135	3.498e-23	***