Revisiting the Cost Escalation Curse of Nuclear Power

New Lessons from the French Experience

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CERNA Mines ParisTech

AMPERE-ADVANCE-PIAMDDI Technology Workshop
Seville, May 27 & 28, 2013

Nuclear power in a low carbon energy future

Nuclear power has been identified as a way to:

1. Enhance energy security
   - Supply significant volumes of base load power
   - Uranium is found at abundance unlike oil and gas
2. Support the transition of fossil-based energy systems to low carbon systems
   - It produces no direct greenhouse gas emissions
   - It has comparable indirect emissions from most renewable energy sources

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Scenarios for nuclear energy

Many energy roadmaps have foreseen an important increase in nuclear power capacity

1. World Energy Outlook (2011) projected an increase from 2009 to 2035
   - Baseline case → 48% (i.e. 549 GWe)
   - New Policies scenario → 70% (i.e. 633 GWe)
   - 450 policy scenario → 130% (i.e. 865 GWe)
2. World Nuclear Association capacity scenarios to 2030 published in 2011
   - Reference case → 65% (i.e. 614 GWe)
   - Upper case → 110% (i.e. 790 GWe)
3. IAEA Nuclear power scenarios for 2050 in the Reference Data Series published in 2011
   - Low scenario → 60% (i.e. 590 GWe)
   - High scenario → 280% (i.e.1415 GWe)

To meet these goals new nuclear power plants will need to be constructed

Can nuclear energy expand quickly enough over the next decades?

- Costs for nuclear power plants are driven primarily by the upfront cost of capital associated with construction (NEA estimates 60% of the LCOE)
  1. Higher scale of investment in an individual nuclear plant compared with other technologies
  2. Larger period required to make a return of investment

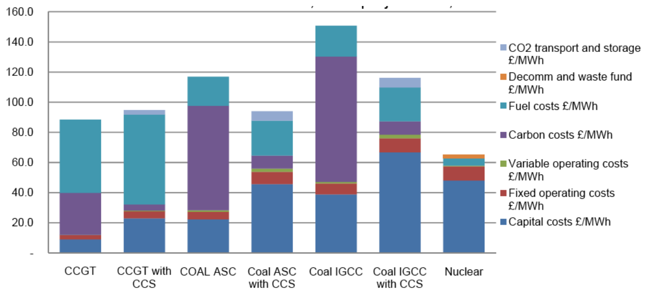

Figure : Levelized cost study for UK DECC UK (2011)

Reducing capital costs is key for nuclear power competitiveness

Concerns about nuclear competitiveness are not unfounded

With the construction of Generation III+ reactors, we can clearly see that they are much more expensive than what they were expected

EPR

1. Olkiluoto-3 in Finland
   - Initial cost prevision in 2003 was €3 billion (€$_{2010}$2.100/kW)
   - Cost revision in 2010 €5.7 billions (€$_{2010}$3.500/kW)
2. Flamanville in France
   - Initial cost prevision in 2005 was €3.3 billion (€$_{2010}$2.200/kW)
   - Cost revision in 2011 €6 billion (€$_{2010}$3.650/kW)
   - Cost revision in 2012 €8.5 billions (€$_{2010}$5.100/kW)

AP1000

1. MIT studies
   - In 2003 the estimated base case overnight cost was USD_{2010} 2.400/ kW
   - In 2009 the range of overnight costs was USD_{2010} 3.650/kW to USD_{2010} 5.100/kW
2. The University of Chicago
   - Updated their forecasts for the AP1000 and estimated and average cost of USD_{2010} 4.210/kW

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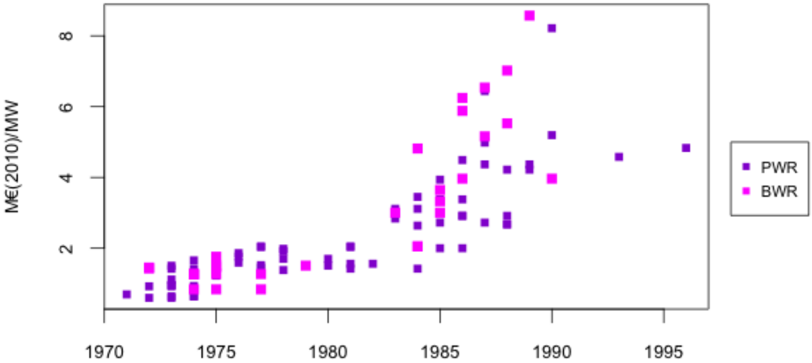
The cost escalation curse

- In the US, the overnight cost in USD_{2010}/MW of the first reactor was almost 7 times less than the cost of the last one



Koomey and Hultman (2007)

Figure : Overnight construction costs for the U.S nuclear fleet

Cost escalation drivers in the U.S Case

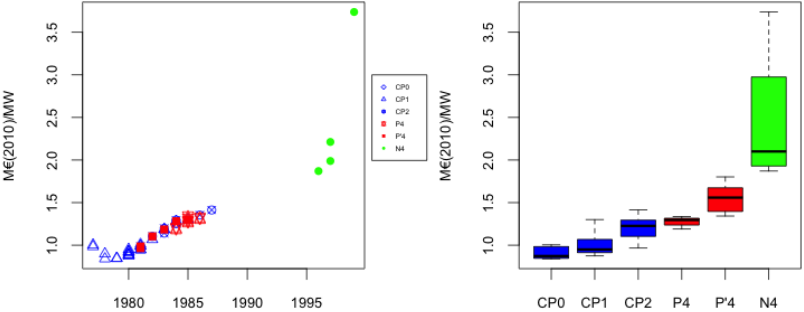
Learning:
- There is no consensus. The diversity of technologies, designs and vendors did not allow achieve significant learning effects
- The learning effects were significant only when the utilities managed their own plants

Scale: Once the endogeneity of leadtime is taken into account, the scale effect is offset.

Regulatory activity: Safety regulation is an important driver for the cost escalation in the U.S. case

Cost Escalation in France

- Despite the favorable institutional setting prevailing in France (i.e. centralized decision making, high degree of standardization and regulatory stability) Grubler (2010) found that the construction costs in FF_{98}/MW for the units installed in 1974 were 3.5 times less than the costs for the post 1990 installed reactors



Grubler (2010)

Figure : Costs for the French nuclear fleet

Revisiting the French Nuclear program with the *Cour des Comptes* data

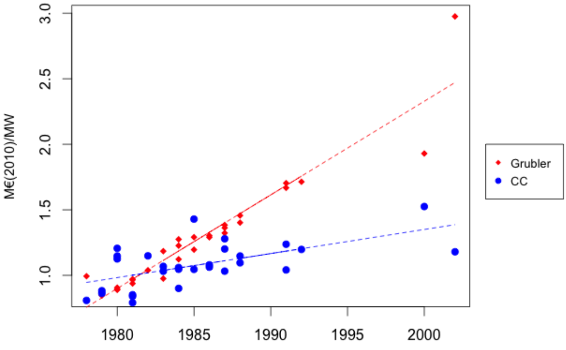


Figure : Grubler's and Cour des Comptes construction costs

Using the actual construction costs from the *Cour des Comptes* report, the escalation is less severe than what was argued

- The average annual rate of growth of the construction costs in €$_{2010}$/MW using Grubler's estimations is equal to 9%
- With *Cour des Comptes* the increase is equal to 3.7% on average per year

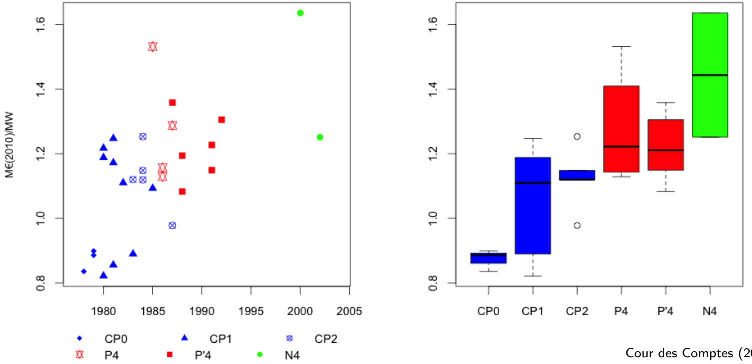
On the French Nuclear Power Program

1. 58 pressurized water reactors (PWR) have been installed within 19 units across France from 1971 to 2002
2. Is possible to distinguish 3 *paliers* and different types of reactors
   - Palier 900 MW has 3 types: CP0,CP1 and CP2
   - Palier 1.300 MW has 2 types: P4 and P′4
   - Palier 1.450 MW only 1 type: N4

Figure : French nuclear power fleet

Cour des Comptes Data

1. Published in January 2012
2. Contains the total investments in €$_{2010}$made on the nuclear power program in France
3. Construction costs are presented by pair of reactors, which means only 29 observations.



Cour des Comptes (2012)

Figure : Cour des Comptes construction costs by palier and type

Model

To identify the main drivers of the cost escalation in the French case, we have assumed the following cost function:

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

Where:

- C_i: Construction cost for the pair of units i in $€_{2010}$ per MW
- Cap_i: Installed capacity in MW
- $ICHT_i$: Labor cost index
- $EXPI_i$: 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

Inflation and labor costs

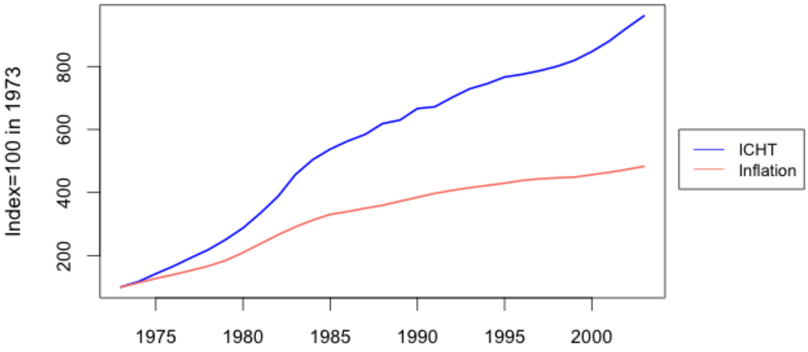


Figure : French GDP price deflector and Labor Cost Index

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Multicollinearity

Table : Correlation Matrix

	Ln Cap	ICHT	EXPI	EXPP	EXPT	UCL	US7
Ln Cap	1.00						
ICHT	0.74	1.00					
EXPI	0.86	0.96	1.00				
EXPP	-0.44	0.18	0.03	1.00			
EXPT	-0.23	0.04	-0.02	0.54	1.00		
UCL	-0.02	-0.35	-0.28	-0.48	-0.50	1.00	
US7	-0.08	-0.26	-0.23	-0.29	-0.21	0.53	1.00

The high correlation between the main explanatory variables implies that:

1. We do not obtain significant results in a linear regression
2. We obtain high Variance Inflation Factors

OLS results

To deal with these limitations, We used a principal component (PCR) approach to deal with the collinearity problem

PCR framework

Loadings and Eigenvalues

Table : Eigenvectors and eigenvalues

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6	Comp 7
Ln Cap	0.441	-0.398	-0.008	0.282	-0.088	0.475	-0.576
Ln ICHT	0.552	-0.086	0.218	-0.229	-0.015	-0.729	-0.232
EXPI	0.553	-0.173	0.165	-0.088	-0.054	0.282	0.738
EXPP	0.106	0.534	0.335	-0.605	-0.076	0.390	-0.256
EXPT	0.095	0.495	0.368	0.643	-0.433	-0.081	0.039
UCL	-0.313	-0.429	0.188	-0.262	-0.781	-0.035	0.016
US7	-0.274	-0.295	0.800	0.103	0.429	0.028	-0.009
λ	81.643	66.622	21.171	14.004	9.840	2.624	0.093

Component 1

- This component explains 41% of the total variance
- It has high loadings from: capacity and cumulative experience.
- It represents what we can called the *big size syndrome*: As nuclear power industry (vendors and utilities) gained experience, bigger reactors were made and this technology scaling-up induced greater complexity which end up in longer leadtimes (Cooper, 2011)

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Component 2

- Accounts for 33% of the variance
- The variables with high loadings are experience within palier and type and the two safety performance indicators
- This component can be thought as a *safety feedback*: Constructing similar reactors (either in size or type) has allowed improvements in terms of the safety indicators

Estimates and results

Table : Principal Component Regression Results

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value	p-value	
LnCap	0.222	1.131	0.106	9.489	1.11e-03	***
Ln ICHT	0.212	0.553	0.536	10.089	7.72e-04	***
EXPI	0.226	0.226	0.020	9.996	4.90e-04	***
EXPP	-0.048	-0.048	0.011	-3.581	4.04e-02	*
EXPT	-0.046	-0.046	0.009	-3.074	1.28e-02	*
UCL	-0.042	-0.042	0.022	-2.677	3.91e-08	***
US7	-0.050	-0.050	0.016	-3.544	2.95e-06	***

Scale:

- Increasing the size of the reactors did not induce smaller unit costs
- We can not discard *pure* economies of scale given that we can not distinguish the size from the complexity effect
- This is a well known phenomenon in nuclear power because the construction of larger reactors is more complex, hence such a project implies longer leadtimes and greater risk of cost overruns

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Experience:

- Cumulated experience had not induced a reduction in costs. This result is often seen as the consequence of nuclear power intrinsic characteristics, i.e. lumpy investments and site-specific design.
- As a new and interesting result, we have found positive learning effects within the construction of similar reactors (Size and Type)
- This result confirms that standardization can be seen as a potential source of savings in the construction of future nuclear reactors

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Safety:

- Reactors with better safety indicators (UCL and US7) are related with higher costs.
- We can deduce that the latest reactors, although more expensive, have also embodied safety improvements.

Ending the curse thanks to standardization

- Construction cost reductions can be achieved when reducing technological variety
- In the French case, we found an example of how the building to the same type of reactors can ease the cost escalation curse
- Our results allow us to conclude that increasing the experience in type will induce lower costs but also better performance in safety
- Is this the future Chinese strategy?

Ending the curse thanks to drastic innovation

- Our analysis using the Cour the Comptes data confirms that the cost escalation in mainly due to the scaling-up strategy
- The scaling-up is associated with grater leadtimes and complexity which in turn meant an increase in cost per MW
- The construction of Generation III+ reactors confirms that larger reactors are likely yo be more expensive again
- What about small modular reactors? Several authors have mentioned some advantages:
  1. They have shorter construction schedules
  2. They have a lower market risk which reduces the cost of capital
  3. Cost savings can be achieved through off-site modules fabrication, as well as the learning by doing after the production of multiple modules

Thank you

Cour de Comptes overnight costs

Cour des Comptes (CC) cost assessment published on 2012 presents the past investments of the 58 PWR EDF reactors by pair of units.

Pair of units	Capacity MW	Year	Type	OC (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
Damprierre1.2	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

Pair of units	Capacity MW	Year	Type	OC (M€2010/MW)
		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

Go back

Linear regressions

Coefficients	Estimate	Std. Error	t value	Pr(> |t|)	
(Intercept)	-38.627	10.273	-3.760	0.0008	***
Year	0.020	0.0051	3.871	0.0006	***

Coefficients	Estimate	Std. Error	t value	Pr(> |t|)
(Intercept)	-21.689806	13.603207	-1.594	0.123
Year	0.009915	0.007506	1.321	0.198
log(Cap)	0.277597	0.219394	1.265	0.217

Coefficients	Estimate	Std. Error	t value	Pr(> |t|)
(Intercept)	-5.724	15.464	-0.370	0.7144
Year	0.002	0.008	0.245	0.8085
log(Cap)	0.209	0.212	0.987	0.3333
log(ReactorsT)	0.072	0.038	1.896	0.0696

Go back

Principal component regression

Some words about PCR:

- With PCR the original q explanatory variables are reduced into a new set of $l < q$ orthogonal variables called principal components
- PCR ranks the new orthogonal variables in order of their importance then we can eliminate least important
- Because the principal components are orthogonal we can perform OLS
- We can use the PRC regression coefficients to get a new set of coefficients that correspond to the original set of variables.

Principal component framework

- Let X^* be the $n \times q$ standardize design matrix
- Let $\lambda_1, \lambda_2, ..., \lambda_k$ be the eigenvalues of the correlation matrix $X^{*\prime}X^*$ and V the $k \times k$ matrix of the normalized eigenvectors associated with each eigenvalue

Recall that the vector λ and the matrix V satisfy the set of homogeneous equations:

$$(X^{*\prime}X^* - \lambda_j I)v_j = 0 \tag{2}$$

Given that $VV' = I$ we can rewrite the linear regression equation as follows:

$$Y = \beta_0^* 1 + X^* VV' \beta^* + u \tag{3}$$

$$Y = \beta_0^* 1 + Z\alpha + u \tag{4}$$

Where:

- $Z = X^* V$ is an $n \times q$ matrix of principal components
- $\alpha = V'\beta$ is a vector of q new coefficients

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Elimination of Principal components

- Note that Z has the same information that X^*, except that the columns are completely uncorrelated with one another and which can be ranked with respect to the magnitude of their eigenvalues λ_j
- The strategy of elimination of principal components should be to begin by discarding the component associated with the smallest eigenvalue because is the least informative.
- An intuitive rule to eliminate components, is doing so until the remaining ones explain some pre-selected percentage of the total variance (for example, 85 percent or more)
- Is possible to use cross-validation as the criteria to select the number of components. We choose l number of components that minimize some MSE.

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