Revisiting the Cost Escalation Curse of Nuclear Power New Lessons from the French Experience

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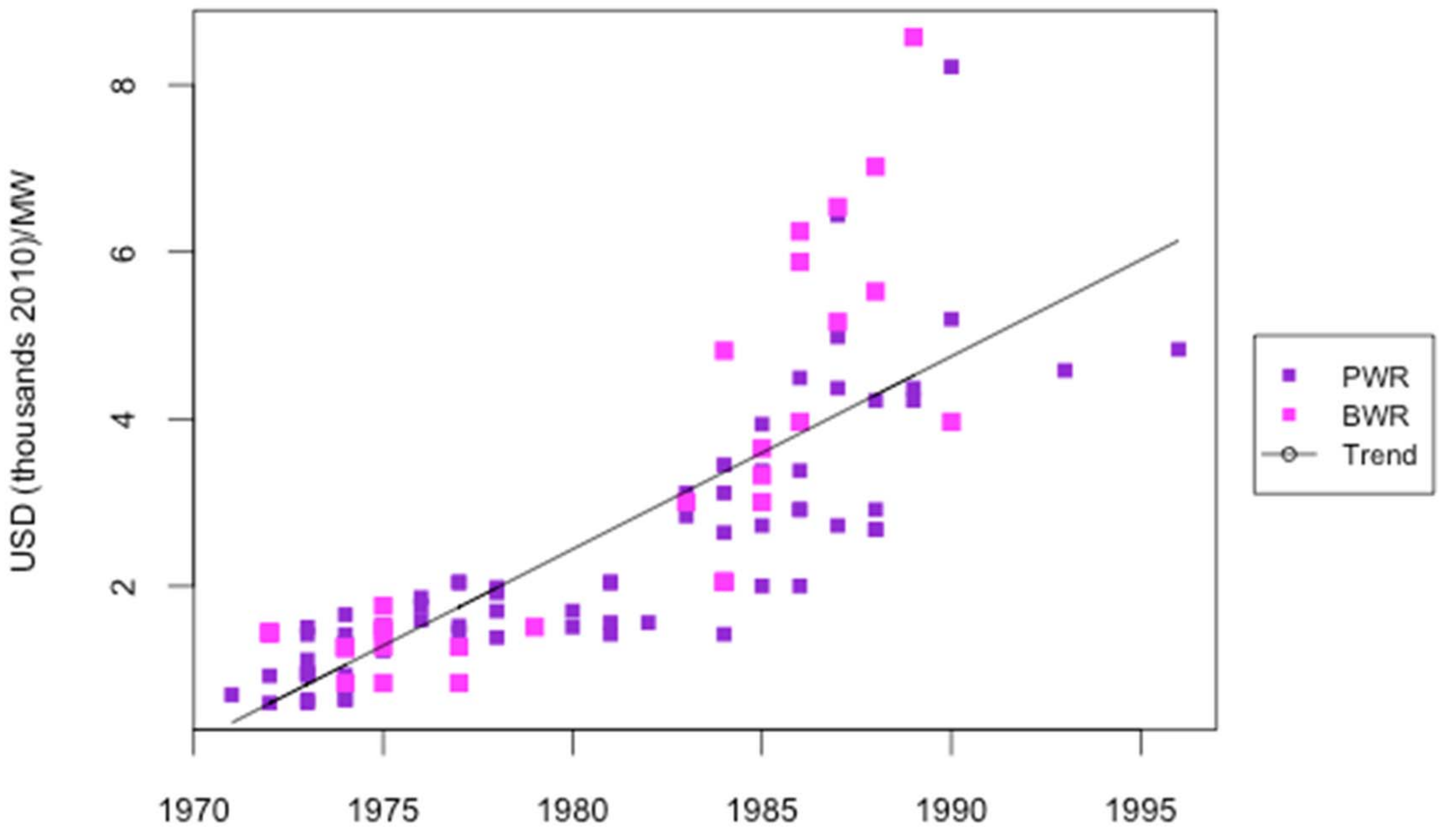
The cost escalation curse

In the US, the overnight cost in USD2010/MW of the first reactor was almost 7 times less than the cost of the last one



Starting again

- EPR

  1. Olkiluoto-3 in Finland

     - Initial cost prevision in 2003 €3 billion ($€_{2010}$ 2.100/kW)
     - Cost revision in 2010 €5.7 billion ($€_{2010}$ 3.500/kW)

  2. Flamanville in France

     - Initial cost prevision in 2005 €3.3 billion ($€_{2010}$ 2.200/kW)
     - Cost revision in 2011 €6 billion ($€_{2010}$ 3.650/kW)
     - Cost revision in 2012 €8.5 billion ($€_{2010}$ 5.100/kW)

- AP1000

  1. MIT studies

     - In 2003 the estimated base case overnight cost was $US\$_{2010}$ 2.400/ kW
     - In 2009 the range of overnight costs was $US\$_{2010}$ 3.650/kW to $US\$_{2010}$ 5.100/kW

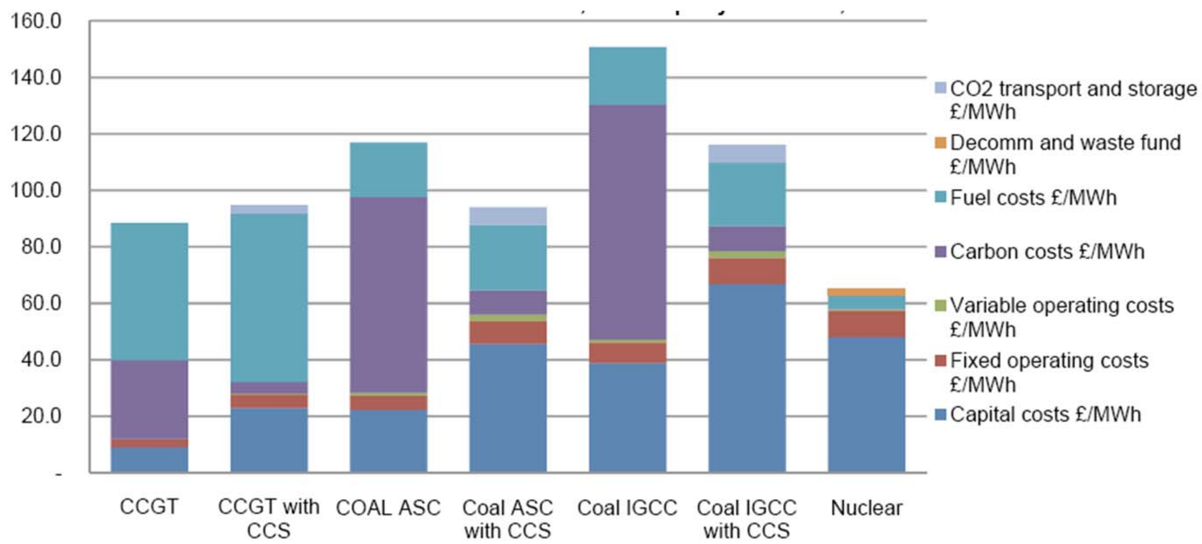
  2 The University of Chicago

     - Updated their 2004 forecast in 2010: for the AP1000 overnight costs has increased from $US\$_{2010}$1950/kW to $US\$_{2010}$ 4.210 kW

New generation reactors have been initially expected to be cheaper than the last variant built (e.g., EPR v. N4) whereas their revised costs based on applications to regulator (AP 1000) or on-going constructions (EPR) are much higher than the most expensive type of reactor ever built in the past

Nuclear power generation is becoming too expensive

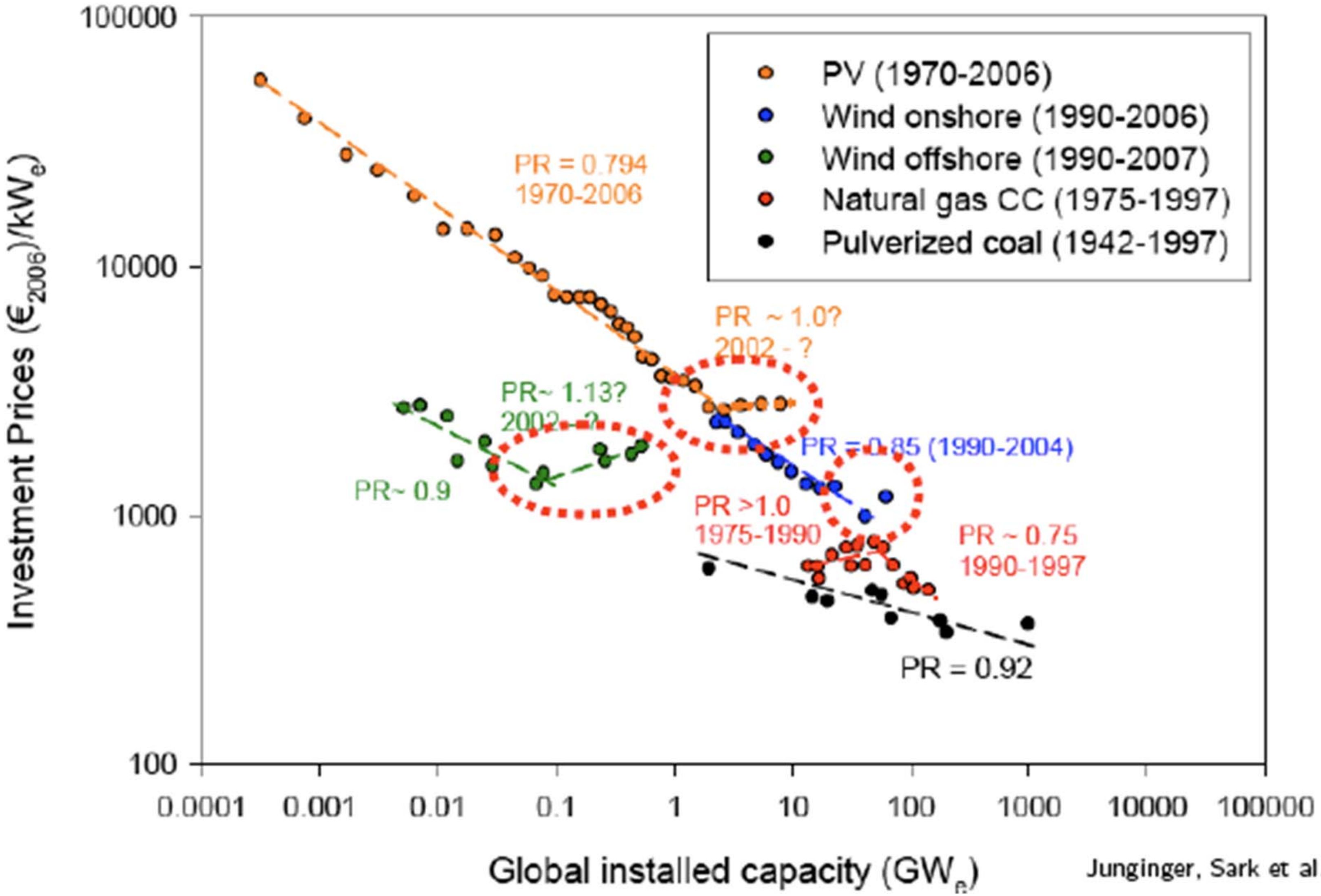
Nuclear power competitiveness mainly depends on construction costs (approximately 60% of the LCOE)



(Source: DECC, UK 2011)

It is critical to identify the means to escape the cost escalation curse for nuclear power to remain a viable option

Decreasing capital costs in other technologies



Junginger, Sark et al. (2010)

Means to achieve reduction of nuclear power plant capital costs

- Scale effects: Can the increase in the size of the plant lead to a reduction in the construction costs per MW installed?
- Modularization: Can the building of more components in factories and less on site reduce construction time and cost?
- Standardization and cumulative experience: Can capital cost reductions be achieved in standardizing plant designs and constructing similar plants in large series?
- Regulation: Can the regulatory framework reduce the risk of cost overruns while providing adequate safety levels?
- Procurement and competition: Can improved competition and procurement contracts result in significant cost reductions?

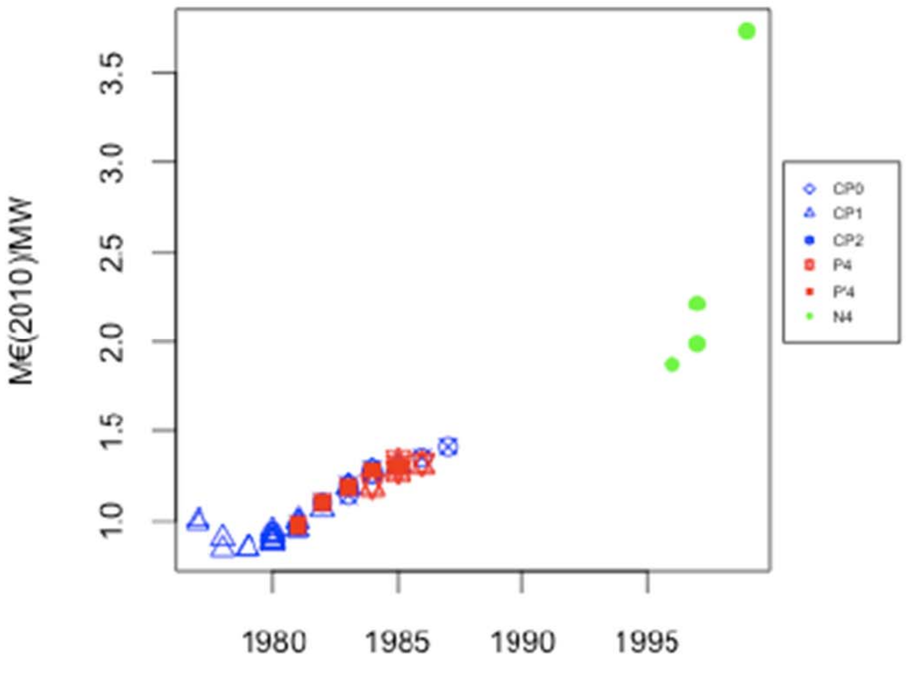
Cost escalation drivers in the U.S. Case

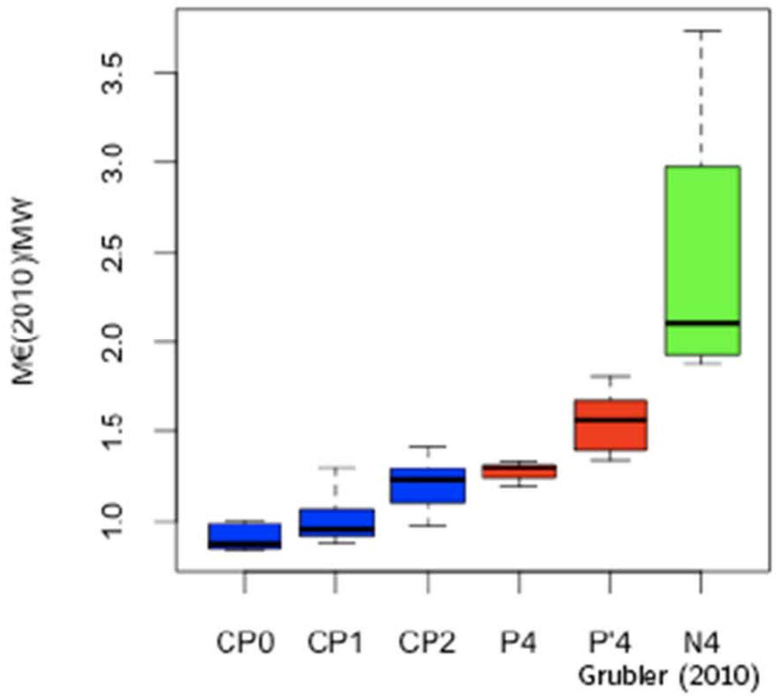
Effect	Komanoff (1981)	Zimmerman (1982)	Cantor &Hewlett (1988)	McCabe (1996)	Cooper(2010)
Scale	-0.2%	+0.17%	+0.13% offsetting by leadtime effect	-0.22% but no significant	+0.94%offsetting by leadtime effect
Learning	-7.0% by doubing the experience	-11.8% first unit -4% second unit	-42% first unit -18% second unit Only for utilities	-9% by 1 unit of builders experience added	0.9% by 1% increase in builders experience
Regulatory	+15.4% +24%	+14% time trend	+10%time trend	Not included	+0.179% NRC Rules +0.096% ΔNRC Rules

- Scale: Once the endogeneity of lead-time is taken into account, the scale effect is offset
- Regulation: Safety regulation instability has been a key driver for the cost escalation
- Learning: There is no consensus. The learning effects were significant only when the utilities have built their own plants

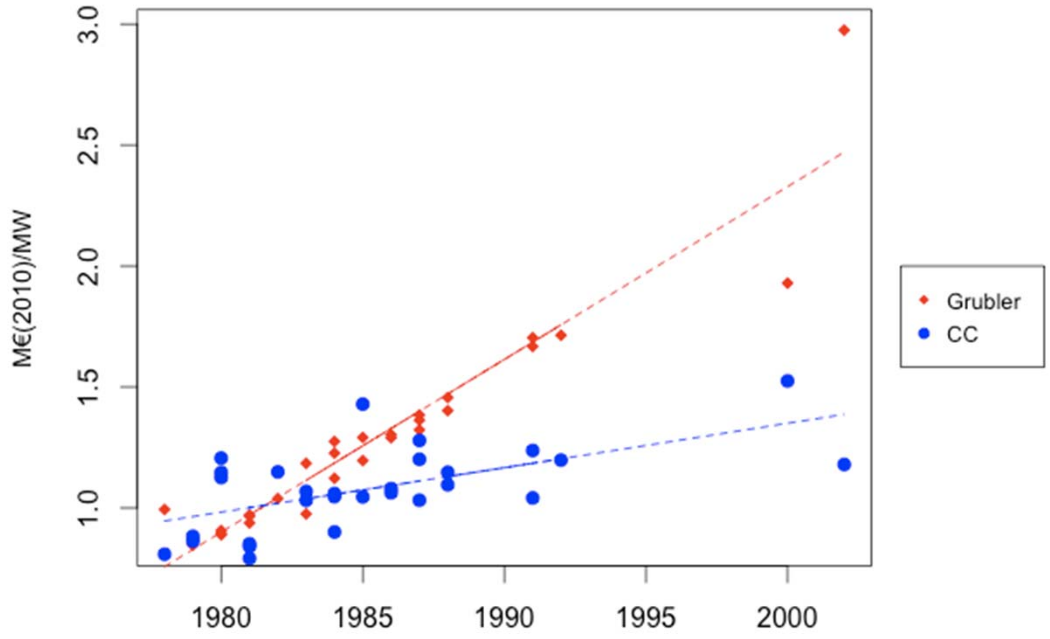
Cost Escalation in France

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 FF98/MW for the units installed in 1974 were 3.5 times less than the costs for the post 1990 installed reactors





Revisiting the French Nuclear program with the Cour des Comptes data



- 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 data it is is equal to 3.7%

On the French Cour des Comptes Data and Nuclear Power Program

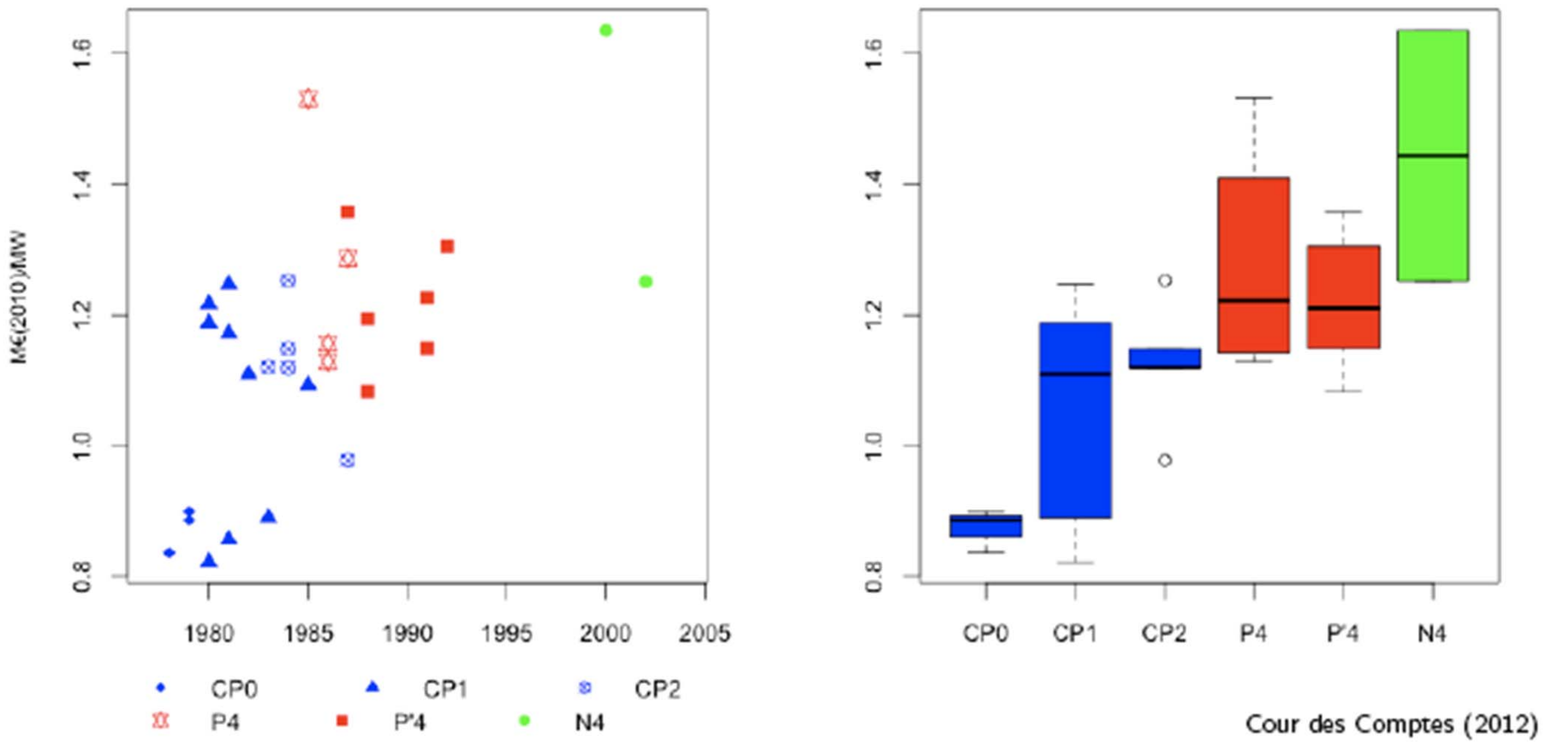
- Cour des Comptes data

  1. Published in January 2012
  2. Contains the total investments in €2010 made on the nuclear power program in France (Construction costs, labor costs, costs before the exploitation)
  3. The construction cost are presented by pair of reactors, which means only 28 observations

- French Nuclear Fleet

  1. The construction of the first reactor began in 1971
  2. The last reactor was connected to the grid in 2002
  3. 58 pressurized water reactors (PWR) have been installed within 19 sites across France
  4. Three *paliers* and different types of reactors
     - Palier 900 MW (CP0,CP1 and CP2)
     - Palier 1.300 MW (P4 and P'4)
     - Palier 1.450 MW (N4)

Cour des Comptes Data



Cour des Comptes (2012)

Model

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

$$\begin{aligned}\ln(C_i) &= \beta_0 + \beta_1 \ln(Cap_i) + \beta_2 EXPI_i + \beta_3 EXPP_i + \beta_4 EXPT_i \\ &+ \beta_5 UCL_i + \beta_6 US7_i + \beta_7 \ln(LTime_i) + u_i\end{aligned}$$

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*

Multicollinearity

Table: Correlation Matrix

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

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

To deal with these limitations, we used a principal component (PCR) approach

Loadings and Eigenvalues

Table: Eigenvectors and eigenvalues

	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

Component 1

- This component explains 41% of the total variance
- High loadings for: capacity, lead-time 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 is associated with greater complexity which ended up in longer lead-times (Cooper, 2011)

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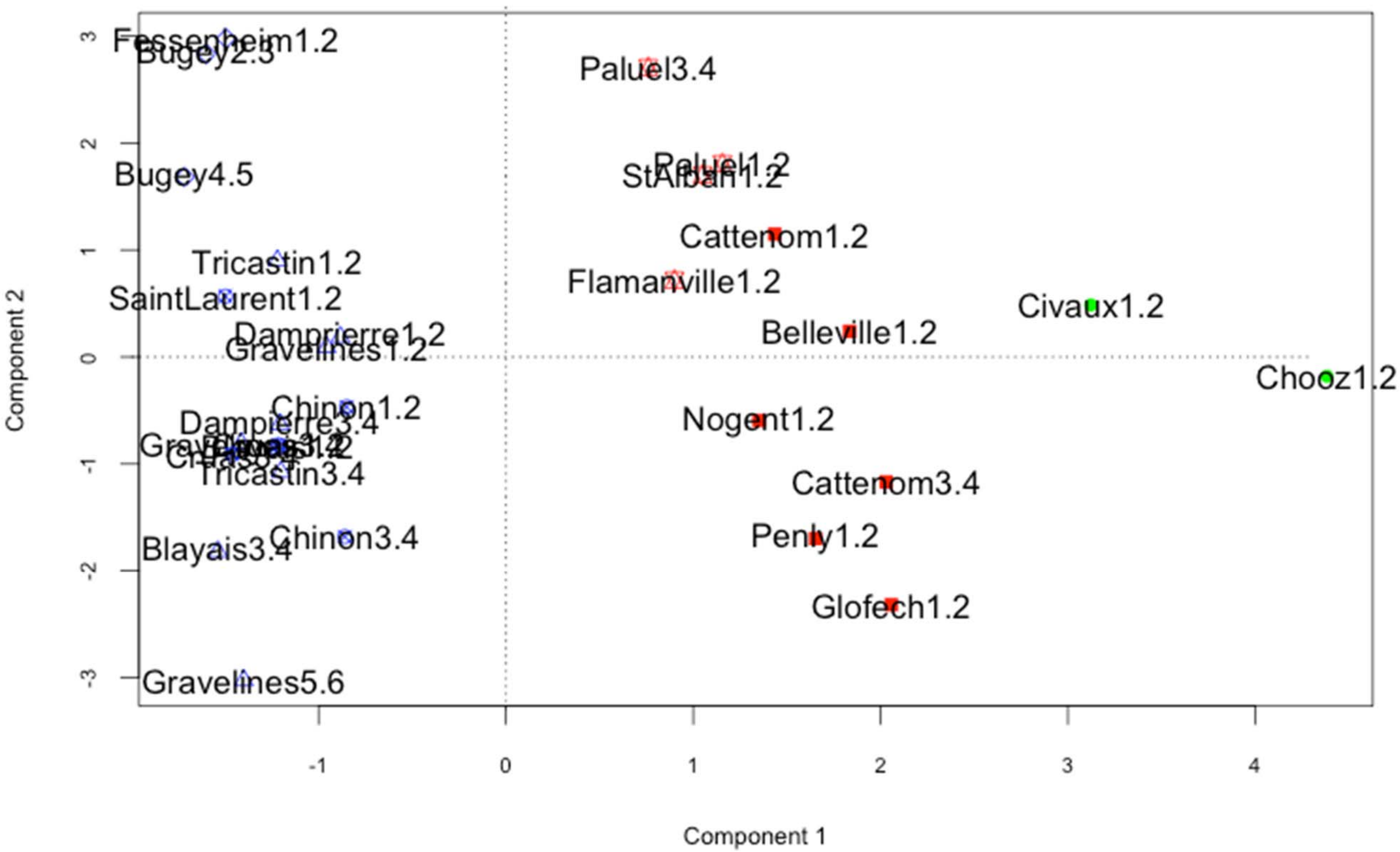
- Component 2
- Accounts for 33% of the variance
- The variables with high loadings are experience within palier and type and the two safety performance indicators
- Constructing similar reactors (either in size or type) has allowed improvements in terms of safety

Principal components



Estimates and results

Table: 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	***

- Scale: Increasing the size of the reactors did not induce smaller unit costs
- This is a well known phenomenon in nuclear power because the construction of larger reactors is more complex, hence such a project implies longer lead-times 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 finding, we have found positive learning effects within the construction of similar reactors (Size and Type)
- This finding 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.
- The latest reactors, although more expensive, have embodied safety improvements

Ending the curse thanks to drastic innovation

- Our analysis using the Cour des Comptes data confirms that the cost escalation is mainly due to the scaling-up strategy
- The scaling-up is associated with greater lead-times and complexity which in turn meant an increase in costs per MW
- The construction of Generation III reactors confirms that larger reactors are likely to be more expensive again
- What about small modular reactors? Several authors have mentioned some advantages:
  - Shorter construction schedules
  - Lower market risk which reduce the cost of capital
  - Potential cost savings due to off-site module fabrication, as well as learning by doing after the production of multiple modules
- Is a paradigm shift possible?

Ending the curse thanks to standardization

- Construction cost reductions can be achieved when reducing technological choice
- In the French case, we found an example of how the building of the same types 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
- The future Chinese strategy?