Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress

Lina Escobar Rangel and Michel Berthélemy

Mines ParisTech - Centre for Industrial Economics CERNA

PSL Séminaire de recherches en économie de l'énergie

Paris, February 12, 2014

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Growing demand for nuclear power...

Demand for nuclear power has increased in the past years and it is likely to keep on rising. According to the WNA(2014), more than **45** countries are considering keep on or embarking upon nuclear programs, broadly we can classify these countries in 3 groups:

- Experienced: USA, UK, Korea, Russia, Czech Republic
- Fast-growing economies: China, India
- Newcomers: Turkey, Vietnam, United Arab Emirates, etc

Financing the construction of new nuclear plants often remains a challenge. Costs for nuclear power plants are driven primarily by the upfront cost of capital associated with construction, and this cost remains highly uncertain.

Box plot for the results (*$EUR_{2012}/kW_{installed}$*)

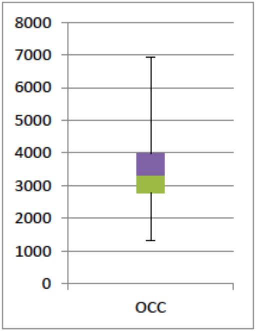

Figure 3.8: Box plot for the 137 data points. The box-plot parameters are listed to the right of the figure

The following parameters apply:

Minimum = 1316 €'12/kW
Median = 3320 €'12/kW
Maximum = 6934 €'12/kW

William D'haeseleer (2013)

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Concerns about nuclear competitiveness are not unfounded

With the construction of FOAK EPR reactors in Europe, we can clearly see that they are much more expensive than initially expected

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}$3.500/kW)
2. Flamanville-3 in France
   - Initial cost prevision in 2005 was €3.3 billion (€$_{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)
3. Hinkley Point C in UK
   - According to the UK Press (The telegraph) the initial cost prevision in 2013 was £16 billion → aprox €19.37 billion for two EPRs

How does the existing literature explain nuclear construction costs?

For the U.S case:

1. Absence of significant learning effects
   - Multiplicity of nuclear vendors, Architect-Engineer (A-E) firms and utilities
   - The diversity in the nuclear models
2. Reduction of economies of scale
   - Bigger reactors meant a raise in lead-times
   - Bigger reactors were subjected to a closer and stricter regulatory monitoring
3. Stricter regulatory requirements

For the French case:

1. Grubler (2011) argues negative learning by doing using estimated costs
2. Lack of public data until 2012, when the *Cour des Comptes* published their report on nuclear costs.
3. Using the actual costs Escobar Rangel and Leveque (2012) found that:
   - The construction costs escalation was smaller than what Grubler estimated
   - The increase in the costs is highly correlated with the increase in the size of the reactors
   - Positive learning effects within specific reactor models.

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Our paper aims to help to answer the following questions

1. Which are the main drivers of the construction costs of new nuclear power plants?
    - Capacity
    - Input prices
    - Regulatory requirements
    - Industrial organization
2. Where can we expect some cost reductions?
    - Scale effects
    - Learning by doing
    - Standardization
    - Innovations

- 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

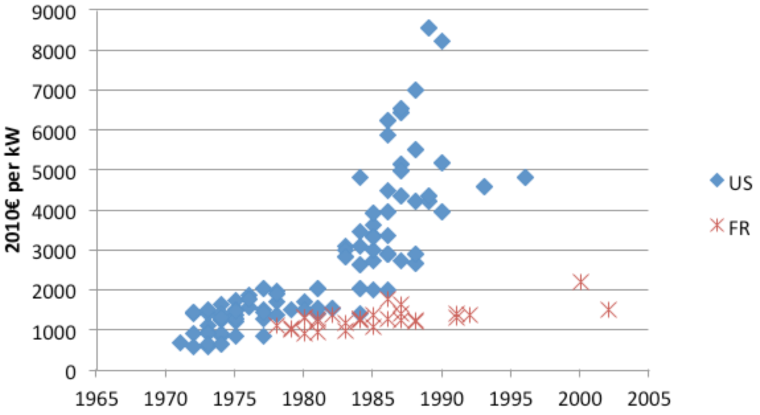

Figure : Overnight construction costs for the French and U.S nuclear fleet

Theoretical model

Rothwell (1986) proposed a theoretical model to study the construction costs of a nuclear power plant. In this model, two firms interact as follows:

- The electric utility seeks to maximize the NPV of the plant by choosing the optimal construction lead-time
- The constructor A-E firm attempts to minimize the cost plant subject to technical constraints and the lead-time

$$Cost = f(LeadTime, Capacity, Prices, error) = \alpha_0 + \alpha_1 ln(LeadTime_i) + \sum_{j=2}^{J} \alpha_j X_{ij} + u_i$$

Leadtimes

- The average lead-time for the U.S nuclear fleet has been 9.3 years
- For France is 6.4 years

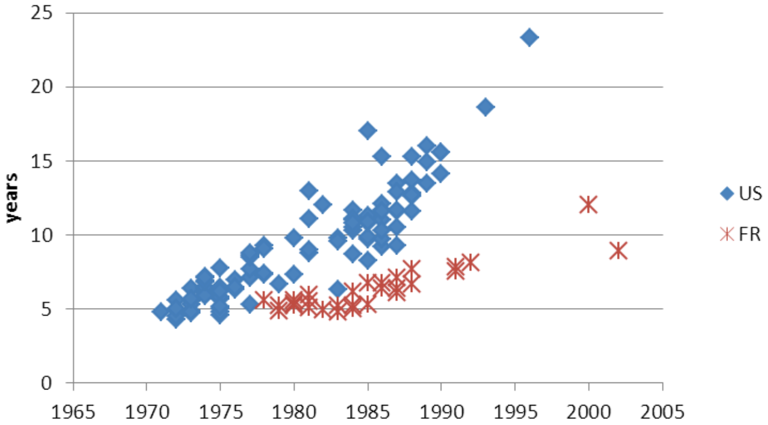

Figure : Construction lead-times for the French and U.S nuclear fleet

IV approach

However, the lead-times can be affected by some unobserved variables that also affect the construction costs (i.e new regulatory requirements) that will bias the estimates in a OLS regression.

To tackle this endogeneity problem, we have to find an instrumental variable that allow us to disentangle the direct effect of the lead-time on the cost equation.

Let's recall some of the desirable properties of an instrumental variable:

1. It makes sense = It is correlated with the endogenous variable (lead-time)
2. It solves the problem = but uncorrelated with the dependent variable (cost)

$$LeadTime = f(Instrument, Capacity, Controls, error) = \beta_0 + \beta_1 ElecDem_i + \sum_{j=2}^{J} \beta_j X_{ij} + \epsilon_i$$

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Model

The system of equations that we estimated is the following:

$$ln(Cost_i) = \alpha_0 + \alpha_1 ln(LeadTime_i) + \sum_{j=2}^{J} \alpha_j X_{ij} + u_i \quad (1)$$

$$ln(LeadTime_i) = \beta_0 + \beta_1 ElecDem_i + \sum_{j=2}^{J} \beta_j X_{ij} + \epsilon_i \quad (2)$$

Explanatory variables: Learning effects

1. To test existence of learning effects, we have considered 4 possible channels:

Table : Variables included in the model to test learning effects

Technology/Firm	A-E firm	Competitors
Same type	ExpArqMo	ExpNoArqMo
Other type	ExpArqNoMo	ExpNoArqNoMo

Explanatory variables: Short run benefits of standardization

2. HHI_i Index of diversity to explore short term standardization gains. It indicates the number of different types of reactors that were under construction when the construction of reactor i began

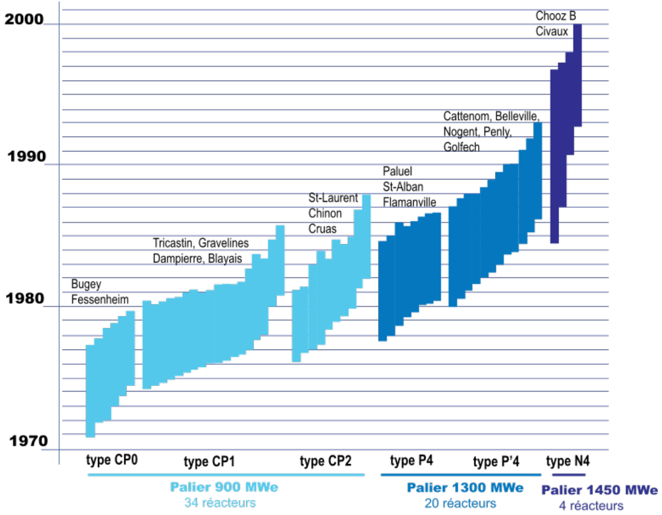
$$HHI_{c,t} = \sum_{m=1}^{M} s_{mtc}^2$$

Where:

- c corresponds to the country
- t corresponds to the year
- m corresponds to the model

$$HHI_i \rightarrow 0 \quad \text{Means low concentration} = \text{highly diverse nuclear fleet}$$
$$HHI_i \rightarrow 10000 \quad \text{Means high concentration} = \text{standardized nuclear fleet}$$

Example



2000
1990
1980
1970
Chooz B
Civaux
Cattenom, Belleville,
Nogent, Penly,
Golfech
Paluel
St-Alban
Flamanville
St-Laurent
Chinon
Cruas
Tricastin, Gravelines
Dampierre, Blayais
Bugey
Fessenheim
type CP0
type CP1
type CP2
type P4
type P'4
type N4
Palier 900 MWe
34 réacteurs
Palier 1300 MWe
20 réacteurs
Palier 1450 MWe
4 réacteurs

Explanatory variables: Technological progress and other controls

3. *Know* that corresponds to the discounted stock of priority patent applications as proxy of innovation
4. Capacity and input prices → as in a Cobb Douglas cost function as controls
5. Dummy variables to control:
   - Country and time fixed effects
   - Changes due to major nuclear accidents *TMI* and *Cherno*
   - Vertical integration between A-E and utility

Result 1: Importance of construction lead-time

Variable	Model 1 Cost		Model 1 Leadtime		Model 2 Cost		Model 2 Leadtime	
ln.*Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln.*ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln.*ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln.*ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln.*ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
HHI_mo	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln.*Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln.*Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

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Result 2: Direct learning effects

Variable	Model 1 Cost		Model 1 Leadtime		Model 2 Cost		Model 2 Leadtime	
ln *.Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln *.ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln *.ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln *.ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln *.ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
HHI_mo	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln *.Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln *.Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

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Result 3: Indirect learning effects

Variable	Model 1 Cost		Model 1 Leadtime		Model 2 Cost		Model 2 Leadtime	
ln .*Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln .*ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln .*ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln .*ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln .*ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
$HHI_m o$	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln .*Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln .*Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

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Result 4: Diversity and short term benefits of standardization

	Model 1				Model 2			
Variable	Cost		Leadtime		Cost		Leadtime	
ln . *Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln . *ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln . *ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln . *ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln . *ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
HHI_mo	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln . *Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln . *Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

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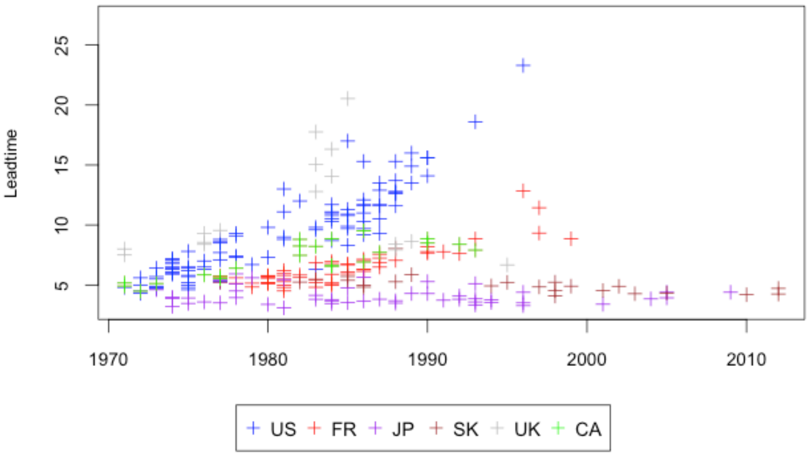
Result 5: Innovations

Variable	Model 1 Cost		Model 1 Leadtime		Model 2 Cost		Model 2 Leadtime	
ln .*Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln .*ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln .*ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln .*ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln .*ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
$HHI_{m}o$	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln .*Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln .*Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

Result 6: Economies of scale

Variable	Model 1 Cost		Model 1 Leadtime		Model 2 Cost		Model 2 Leadtime	
ln .*Leadtime*	1.933	***			1.064	*		
	(0.580)				(0.622)			
ln .*ExpArqMo*	-0.142	***	0.009		-0.149	***	0.009	
	(0.038)		(0.011)		(0.034)		(0.011)	
ln .*ExpArqNoMo*	0.025		0.026	***	0.029		0.026	***
	(0.034)		(0.009)		(0.031)		(0.009)	
ln .*ExpNoArqMo*	0.046		0.010		0.038		0.010	
	(0.039)		(0.012)		(0.035)		(0.012)	
ln .*ExpNoArqNoMo*	-0.068		0.141	***	-0.039		0.141	***
	(0.096)		(0.017)		(0.087)		(0.017)	
$HHI_{m}o$	0.454		-0.566	***	0.374		-0.566	***
	(0.537)		(0.160)		(0.485)		(0.160)	
ln .*Know*					1.416	***		
					(0.522)			
ln *Cap*	-0.769	***	0.125	**	-0.624	***	0.125	**
	(0.192)		(0.053)		(0.182)		(0.053)	
Arq.Utility	-0.256	***	0.009		-0.285	***	0.009	
	(0.093)		(0.028)		(0.085)		(0.028)	
ln .*Demand*			-1.235	***			-1.235	***
			(0.113)				(0.113)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

Construction lead-times in OECD countries



Construction lead-times in OECD countries

Variables	(1) (ln LT)		(2) (ln LT)	
$HHI.Mo_i$	-0.291	**	-0.472	***
	(0.135)		(0.182)	
ln Cap_i	0.395	***	0.254	***
	(0.052)		(0.052)	
$ExpArqMo_i$	0.019		-0.008	
	(0.032)		(0.029)	
ln $EDem_i$	-16.970	***	-21.219	***
	(2.866)		(3.265)	
ln $NPP.UC_i$	-0.020		-0.054	
	(0.033)		(0.047)	
$Tmi.US$	0.432	**	0.439	***
	(0.044)		(0.062)	
$Tmi.Abroad$	0.139	***	0.142	**
	(0.054)		(0.061)	
Cherno	0.188	***	0.214	***
	(0.029)		(0.027)	
Constant	1.105	***	1.977	
	(0.402)		(0.440)	
Country FE	Yes		Yes	
Time FE	No		Yes	
Trend + Trend^2	Yes		No	
Obs.	286		286	
Adj. R^2	0.840		0.869	
Note: Robust standard errors in parentheses				

Conclusion

1. Standardization is a key criterion for the economic competitiveness of nuclear power
   - Reducing diversity has a short term benefit through a reduction in lead-times, the latter being one of the main drivers of construction costs
   - Positive learning effects are conditional on the standardization considering that they only take place through reactors of the same models built by the same firm
2. There is a trade-off between reductions in costs enabled by standardization and potential gains from adopting new technologies with better operating and safety performance → Optimal pace of technological change

Thank you for your attention