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

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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.

Experienced countries: US, UK, Russia, South Korea

According with UK's Department of Energy & Climate Change nuclear industry plans to develop around 16 gigawatts (GW) of new nuclear

- EDF → 4 EPRs (6.4GW) at Hinkley Point and Sizewell
- Hitachi → 2 or 3 new nuclear reactors at Wylfa and Oldbury
- NuGeneration → 3.6GW of new nuclear capacity at Moorside

Fast-growing economies: China, India

China has 28 reactors under construction and it is planned a three-fold increase in nuclear capacity to at least 58 GWe by 2020, then some 150 GWe by 2030

- 16 AP1000 reactors are planned to start to be constructed from 2014-2018
- At least 6 ACC1000 in 4 different locations
- 2 EPRs in Guangdong
- Other technologies like VVER-1000, VVER-1200, CNP-600, etc are also envisioned

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...but how much does nuclear power cost?

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 (*$EUR_{2012}/kW_{installed}$*)

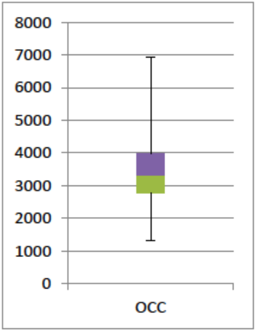

Figure 3.8: Box plot for the 137 data points. The box-plot parameters are listed to the right of the figure

The following parameters apply:

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

William D'haeseleer (2013)

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

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What can we learn from the experience from the two largest nuclear fleets in the world?

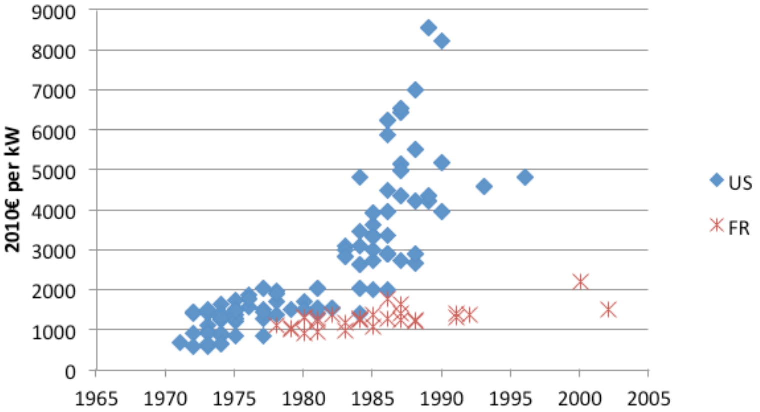

Figure : Overnight construction costs for the French and U.S nuclear fleet

Goal of our paper

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

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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

$$LeadTime = f(Expected\ demand, Capacity)$$
$$Cost = f(LeadTime, Capacity, Prices)$$

Leadtimes

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

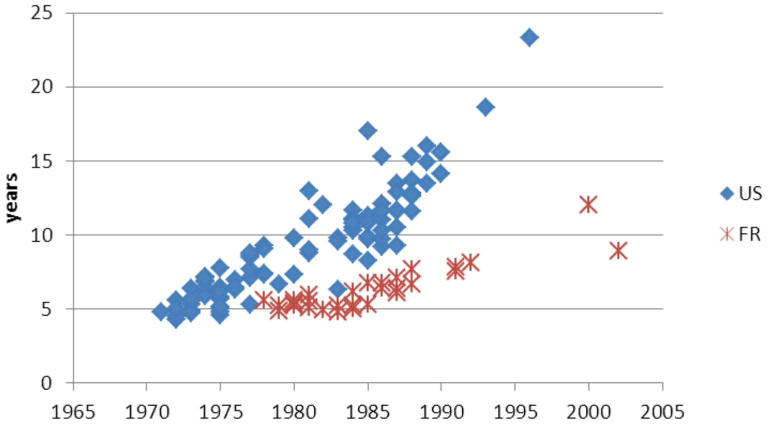

Figure : Construction lead-times for the French and U.S nuclear fleet

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Model

The system of equations that we estimated is the following:

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

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

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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

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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

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

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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

Regression results

	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)	
$HHI_m o$	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)	
TMI.US	-0.058		0.272	***	0.115		0.272	***
	(0.184)		(0.0431)		(0.179)		(0.043)	
TMI.FR	-0.015		-0.028		-0.064		-0.028	
	(0.246)		(0.074)		(0.223)		(0.074)	
Cherno	-0.077		0.058	*	-0.030		0.058	*
	(0.123)		(0.031)		(0.113)		(0.031)	
Constant	6.420	**	-2.347	***	-4.182		-2.347	***
	(2.915)		(0.448)		(4.767)		(0.448)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend²	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.833		0.955		0.866		0.955	

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Where can we expect cost reductions?

Result 1: Existence of learning effects

Our results allow us to conclude:

1. There are positive learning effects in the construction of nuclear power plants, but they are conditional to the same type of reactor
2. On average, we can expect a 12.4% reduction in the construction costs for the second unit of a reactor model built by the same A-E firm

Variable	Cost		Leadtime
ln .*Leadtime*	1.064	*	
	(0.622)		
ln .*ExpArqMo*	-0.149	***	0.009
	(0.034)		(0.011)

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Result 2: Short term benefits from standardization

The coefficient of the regression tells us that:

1. The construction of an homogeneous nuclear fleet reduces the risk of delays
   - Better coordination of supply chains
   - Reduces the risk of regulatory intervention
2. These short term benefits of standardization disappear when the nuclear fleet under construction is diverse
3. On average we can expect that with a 10% increase in the HHI index (less diversity), the costs will be reduced in 22%

Variable	Cost		Leadtime	
ln *.Leadtime*	1.064	*		
	(0.622)			
$HHI_m o$	0.374		-0.566	***
	(0.485)		(0.160)	

Result 3: Scale effects

By using the data form the U.S and France

1. Even if larger reactors toe longer to built they are cheaper per MWe
2. On average we can expect that a 10% increase in capacity will reduce the costs by 5.27%

Variable	Cost		Leadtime	
ln *.Leadtime*	1.064	*		
	(0.622)			
ln *Cap*	-0.624	***	0.125	**
	(0.182)		(0.053)	

How can we explain the cost escalation?

Result 4: Innovations

Contrary to what have been observed in other energy technologies:

1. Innovations in nuclear power is one of the main drivers of the construction costs:
   - Nuclear vendors have seek to improve the operating performance of their reactors
   - Innovation has also been driven by the requirements of nuclear safety authorities
2. Long term trade-off: We have better reactors, however they are more expensive

Variable	Cost		Leadtime
ln *.Know*	1.416 (0.522)	***	

Result 5 Technological diversity

1. The experience gained in other models is not directly transferable to any project
2. The continuous delays in the construction of the EPR in France is an example of these results

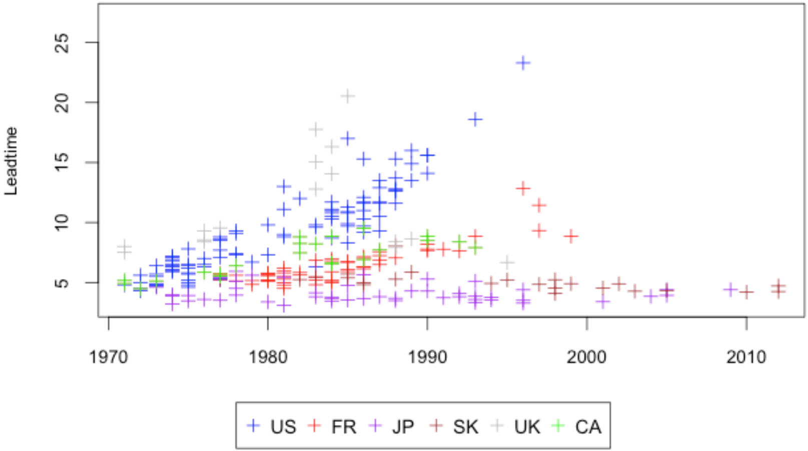
Variable	Cost		Leadtime	
ln .*Leadtime*	1.064	*		
	(0.622)			
ln .*ExpArqNoMo*	0.029		0.026	***
	(0.031)		(0.009)	
ln .*ExpNoArqNoMo*	-0.039		0.141	***
	(0.087)		(0.017)	

Result 6 Accidents

1. Delays in the construction linked with major nuclear accidents have played its role in the cost escalation
2. Safety regulation impacts construction costs and lead-time through other dimensions than technological change. TMI and Chernobyl accident had a negative impact on the lead-times.

Variable	Cost		Leadtime	
ln .*Leadtime*	1.064	*		
	(0.622)			
TMI.US	0.115		0.272	***
	(0.179)		(0.043)	
TMI.FR	-0.064		-0.028	
	(0.223)		(0.074)	
Cherno	-0.030		0.058	*
	(0.113)		(0.031)	

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