Estimating nuclear cost: methodology and econometric evidence

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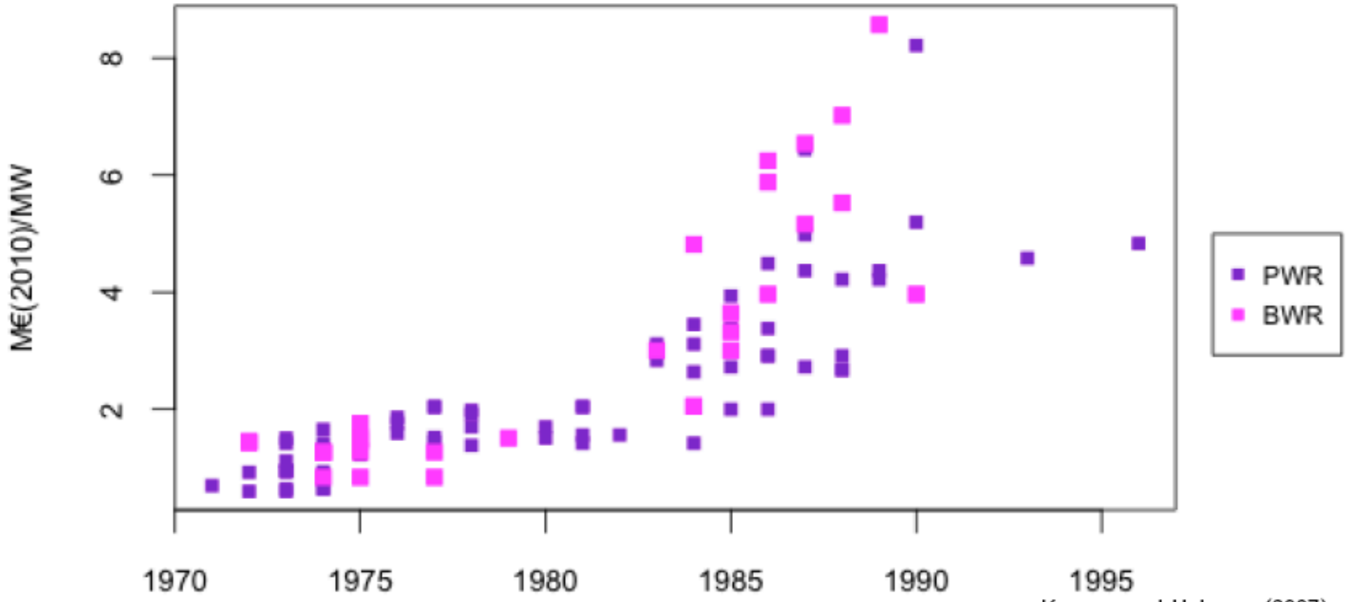
Introduction

- Nuclear costs need to be assessed
  - For regulation purpose (e.g., cost-plus regulation of US utilities, wholesale nuclear tariff imposed to EDF in France, bojunggeso in Korea?)
  - For investment decision made by private investors (is nuclear power profitable?) or by government (is nuclear power socially beneficial?)
  - To compare nuclear with other power generation technology (is nuclear power generation competitive?)
- How to assess nuclear costs?
- What past building costs tell us?

Is there a cost escalation curse?

In the US the overnight cost in USD_{2010} of the first reactor was almost 7 time less than the cost of the last one



Generation III + reactors seem to be much more expensive than expected:
Olkiluoto-3 in Finland, initial cost prevision in 2003 €3 billions, cost revision in 2010 €5,7 billions
Flamanville in France, , initial cost prevision in 2005 €6 billions, cost revision in 2012 €8,5 billions

Outline

- Methodological aspects
  - Definition of costs (opportunity cost, social cost, external costs, private costs)
  - Counterintuitively, decommissioning costs, waste costs, and expected costs of accident are insignificant
  - Key cost drivers: overnight costs, discounting rate, load factor, CO2 price
  - The levelized cost of electricity method
- Empirical evidence from past building costs
  - US and French data
  - Learning effects
  - Lead time and buildings costs

What is cost?

- Economists are not accountants
- Opportunity costs
- The cost of *doing* something not of something
- The cost is not an objective dimension as mass in physics
- It depends on the agents, his preferences and her set of options

Main types of costs

- Private cost
  - How much EDF or KHNP will pay for a new build?
- Social cost: costs incurred by the market participants + costs to others
- External costs
  - CO_2 emissions
  - What is the cost of a nuclear accident?
  - No monetary benefits (energy security and independence)

Social and private discounting rate

- For a private investor, what does matter is the cost of capital (debt and equity)
- For a country's choice to embark in a long term technology and infrastructure the value of one $ tomorrow (say 30 or even 100 years) as expressed in one $ today depends on
  - p=the pure preference rate for the present
  - e=the elasticity of the marginal utility of consumption
  - g=the expected growth rate per capita
- d=p+eg
  - [2;2;3], d=8%, 100 today discounted over 100 years = 0,40
  - [1;1;1], d=2%, 100 today discounted over 100 years = 14

The end of cycle costs

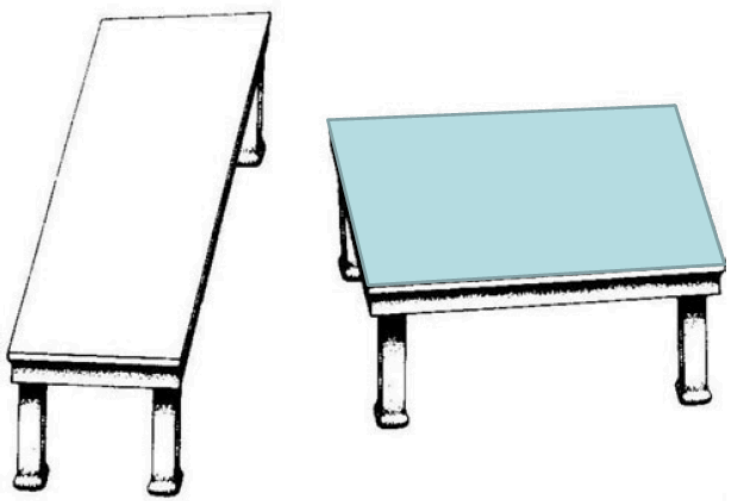
- For a new build, the costs of waste treatment and decommissioning are not important because of the discount rate
  - Suppose that decommissioning would cost 15% of the cost of a new reactor, this share will only represent 0,7% of the total cost if work take place 40 years after construction with a 8% discount rate

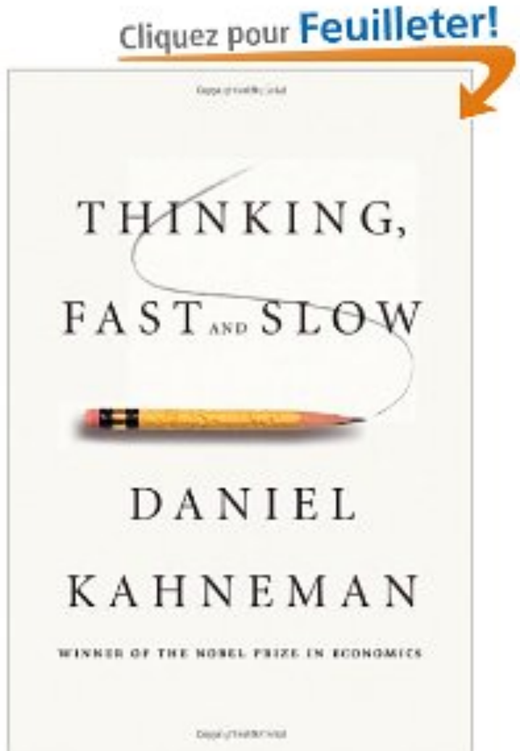
Costs of accidents

- Cost of insurance is generally low because liability is generally limited and insurance only partial
  - France liability cap at €90 million; soon €700 million
  - UK liability cap €150 million; soon € 1,2 billion
- Expected cost estimation with high figures, on the back of the envelope
  - €1 trillion damages, 10^{-5} probability of a core meltdown with massive release per reactor.year, annual production of a reactor amounts to 10 million MWh, the expected cost=€1 par MWh (0,00001x1,000,000,000,000)
- So full internalization of risk of catastrophe would only result in a slight increase in the cost of nuclear electricity
- However, variability of the costs of nuclear accidents is huge and probability analysis does not applied to unknown unknows (i.e., black swans) and perceived probability of dread risks are biased

Perception of probabilities is biased

- As optical illusion





Biases of perception are all unfavorable to nuclear technology

- Nuclear accident is a
  - Rare event, hence perceived probability is overestimated
  - Ambiguous event, hence our minds select on the highest value of probability and damages
  - Dread event, hence we neglect the denominator and focus on the event itself which leave a strong footprint
- Consequently,
  - Demand for overinvesting in nuclear safety
  - Distorted choice between alternative power technologies (coal or hydro are perceived less dangerous whereas deaths due to coal or hydro have been higher)
- Do we have to take into consideration in the nuclear social cost, the expected cost of accident or the perceived cost of accident?

CO2 cost

- Nuclear power generation does not emit CO_2
- So nuclear cost has to be compared with CO_2 emitting technologies in including a CO_2 cost for these technologies
- But what is the CO_2 cost?
  - The amount of CO_2 tax or tradable emission permits, when there is one?
  - The estimation given by experts: from 15$/t to 300$/ ?
- The cost of CO_2 is key when assessing nuclear competitiveness vis-à-vis coal or gas

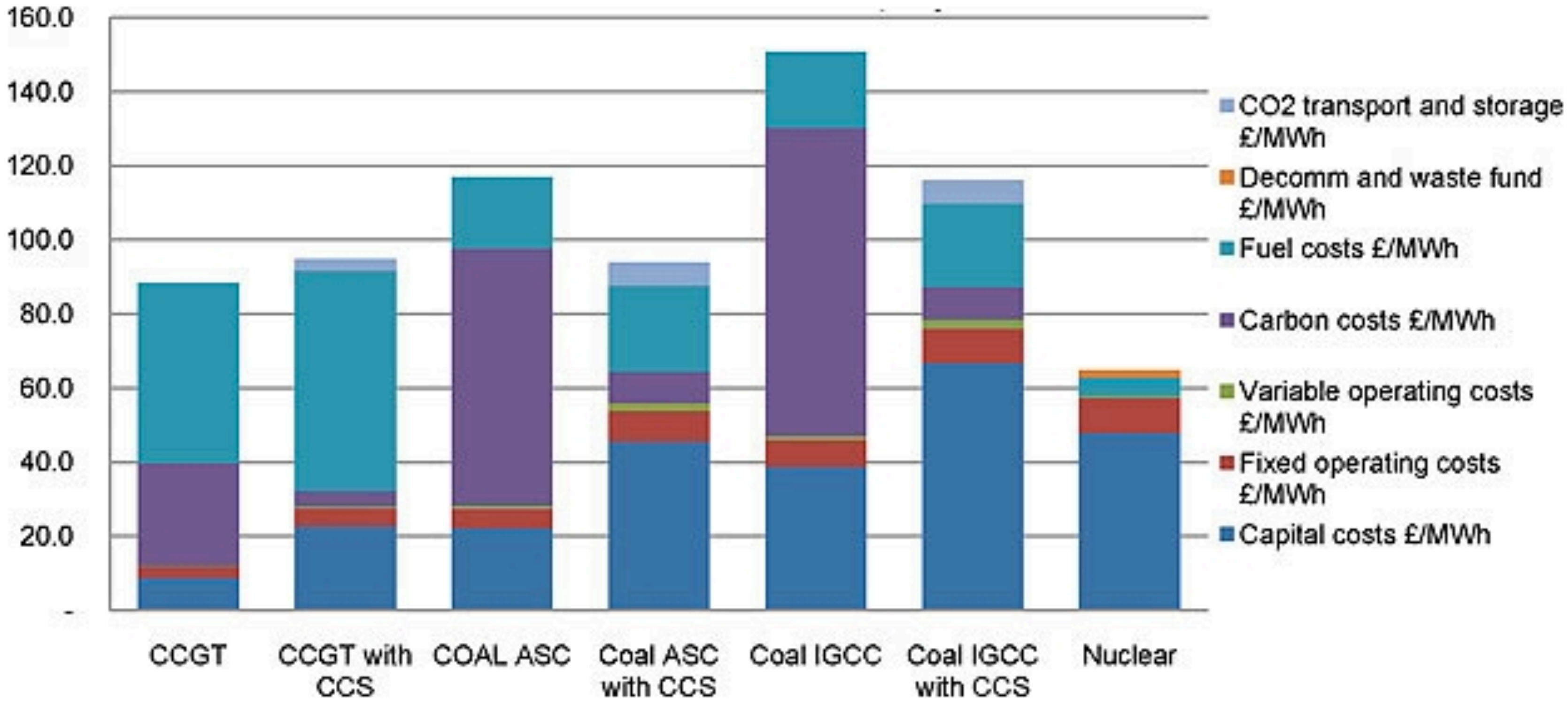
Other key factors of nuclear costs

- Overnight construction cost
  - MIT study (2003)$\$_{2010}$2400/kW
  - MIT study (2009) $\$_{2010}$5100/kW)
- Discount rate: 5%, 10%, more?
- Construction time: 5 years, 7 years, 10 years?
- Load factor: 92% in South Korea, 90% in the US, 70% in Japan?
- [$2000 per kWe; 5 years, 95%, 5%]= $34/MWh
- [5000 per kWe; 6 years, 85%, 12%]=$161,5/MWh

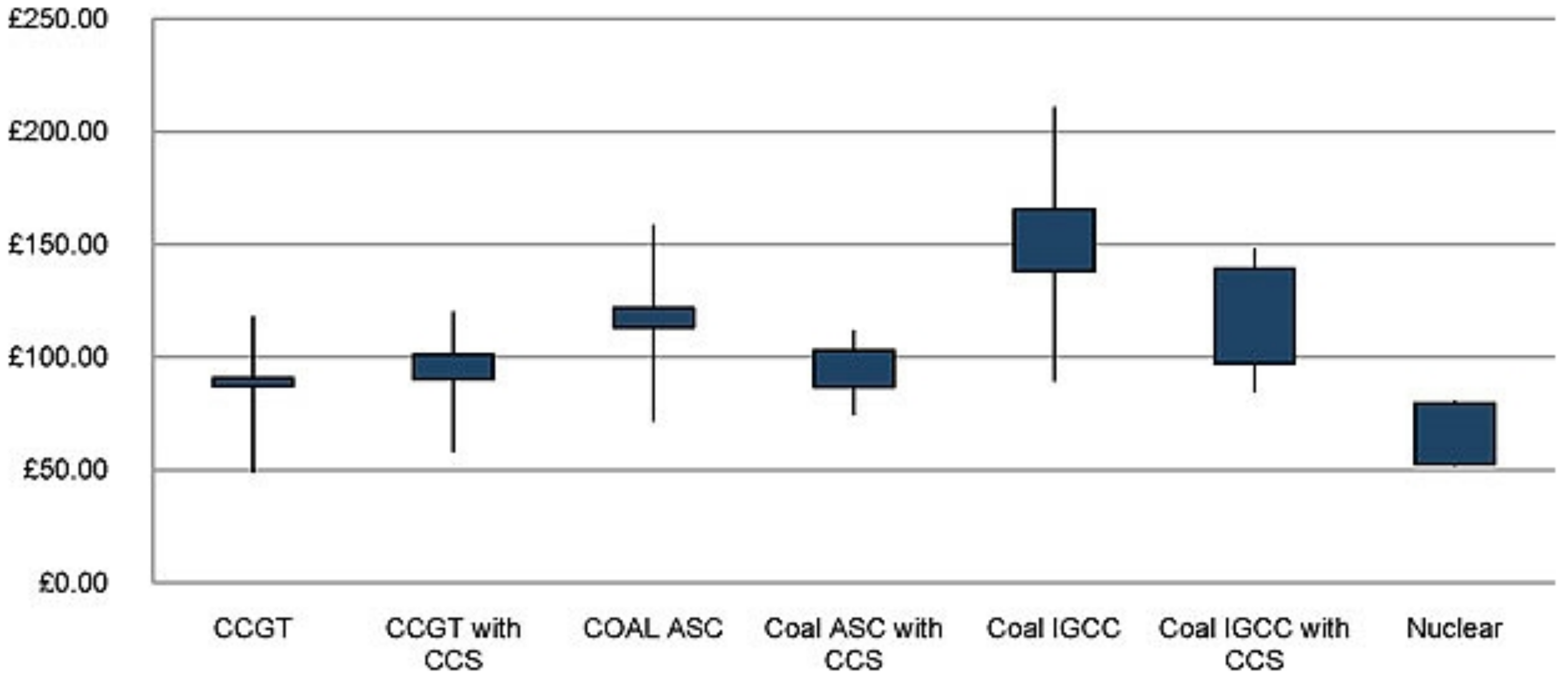
The levelized cost valuation method

- Discounting cash flow analysis: discounting to present value all the future cash-flows and accumulating them to find the net present value of the investment
- The levelized cost methodology reverses the approach: what is the required annual revenues so that the present value of all revenues exactly balances the present value of project costs
- = the average price of electricity that would have to be paid by consumers to repay exactly the investor (or operator) for the capital, operation and maintenance and fuel expenses, with a rate of return equal to the discount rate

Levelized cost UK study (DECC, 2011)

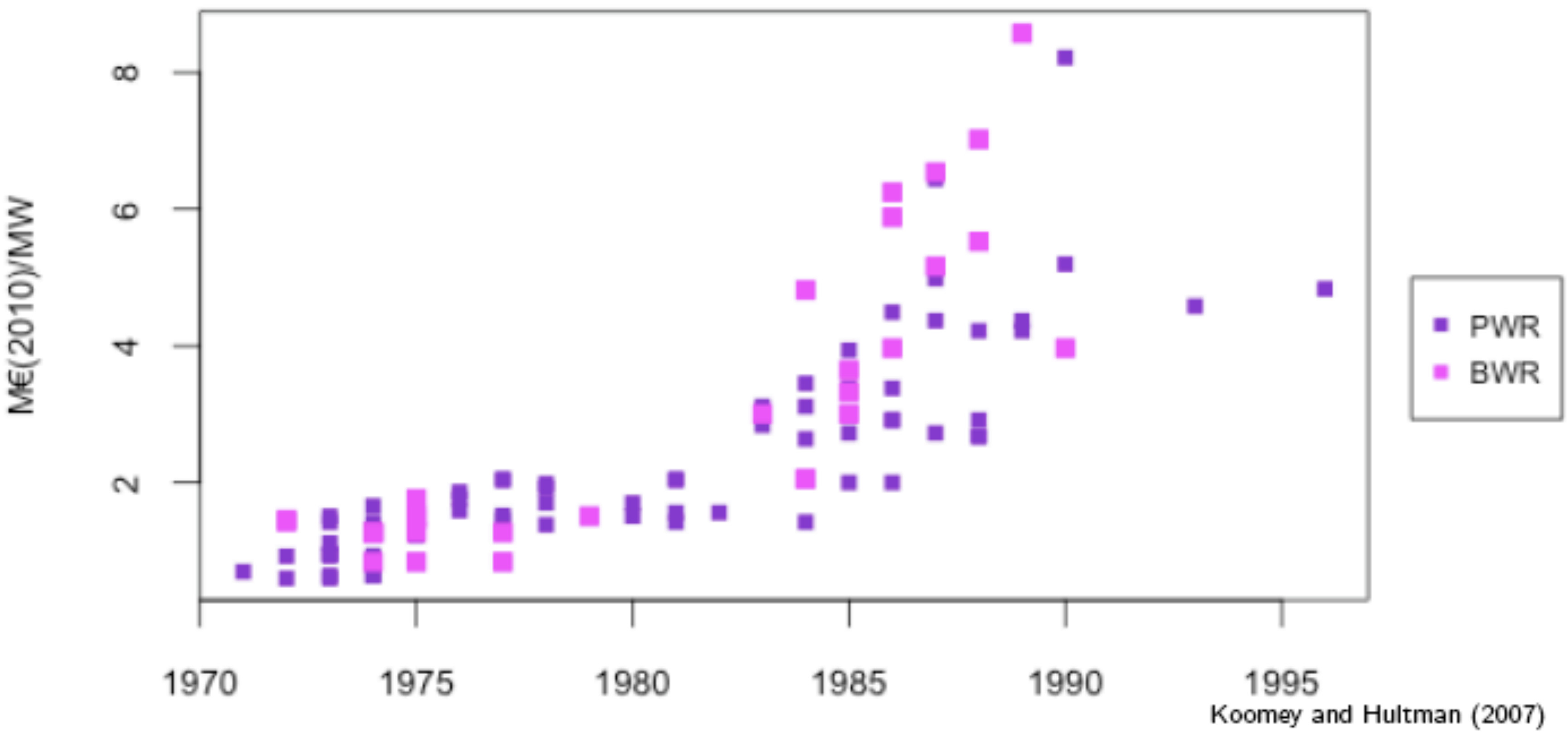


Sensitivities (solid bars high/low CAPEX figures; thin bar high/low estimate sof CAPEX, fuel and CO2 price)

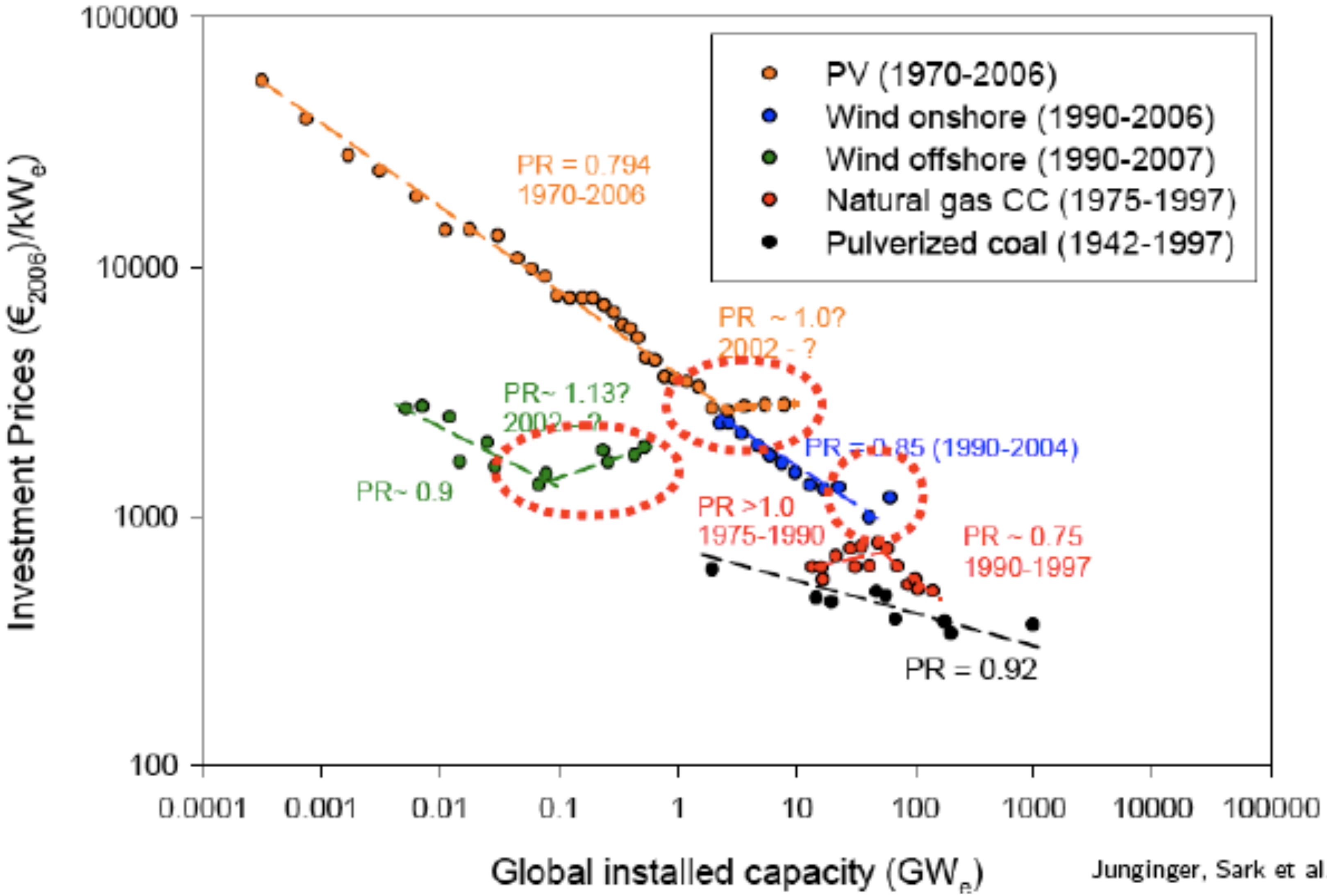


Evolution of the U.S nuclear construction costs

- 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



Decreasing capital costs in other technologies



Junginger, Sark et al. (2010)

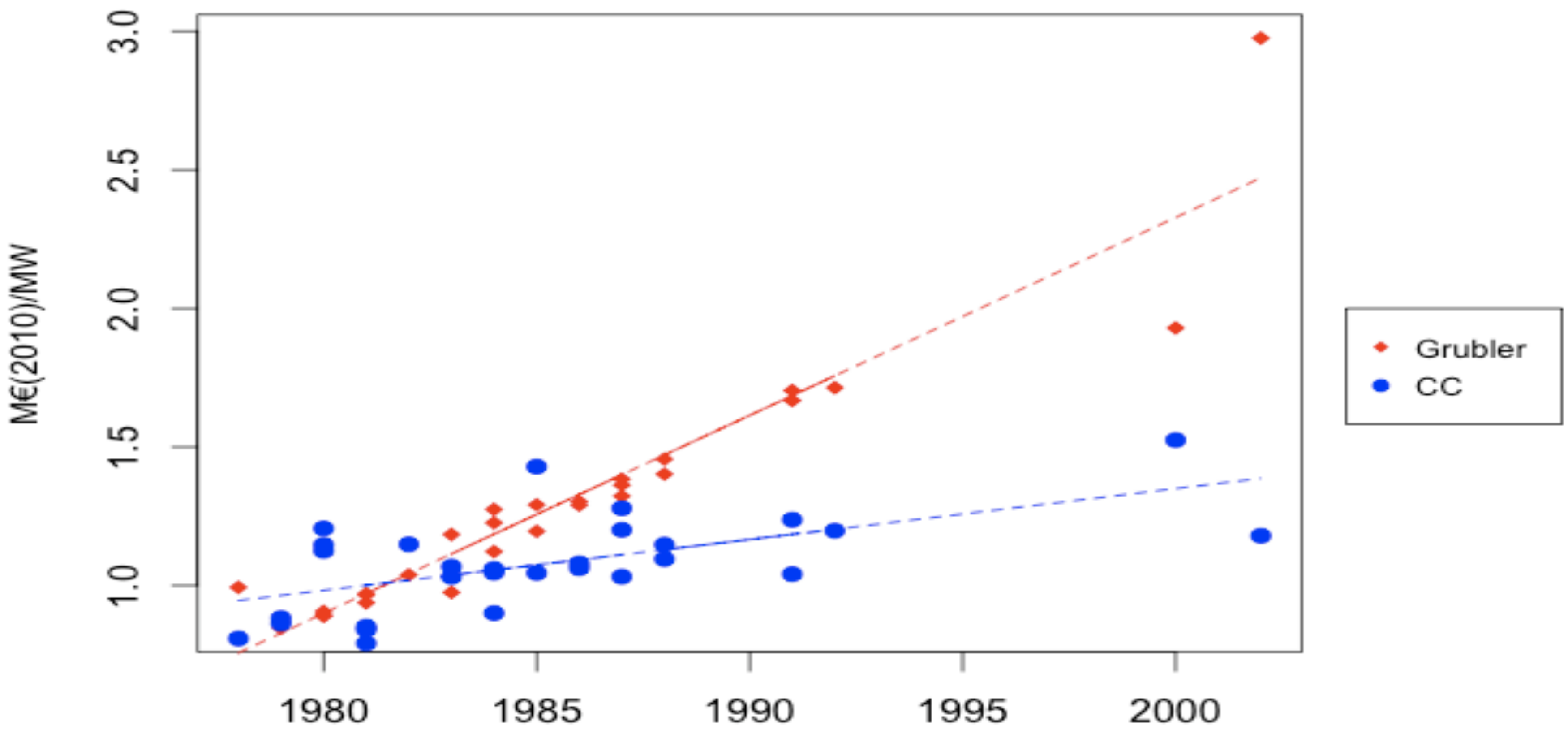
Findings for the U.S nuclear fleet

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% NCR Rules +0.096% ΔNCR Rules

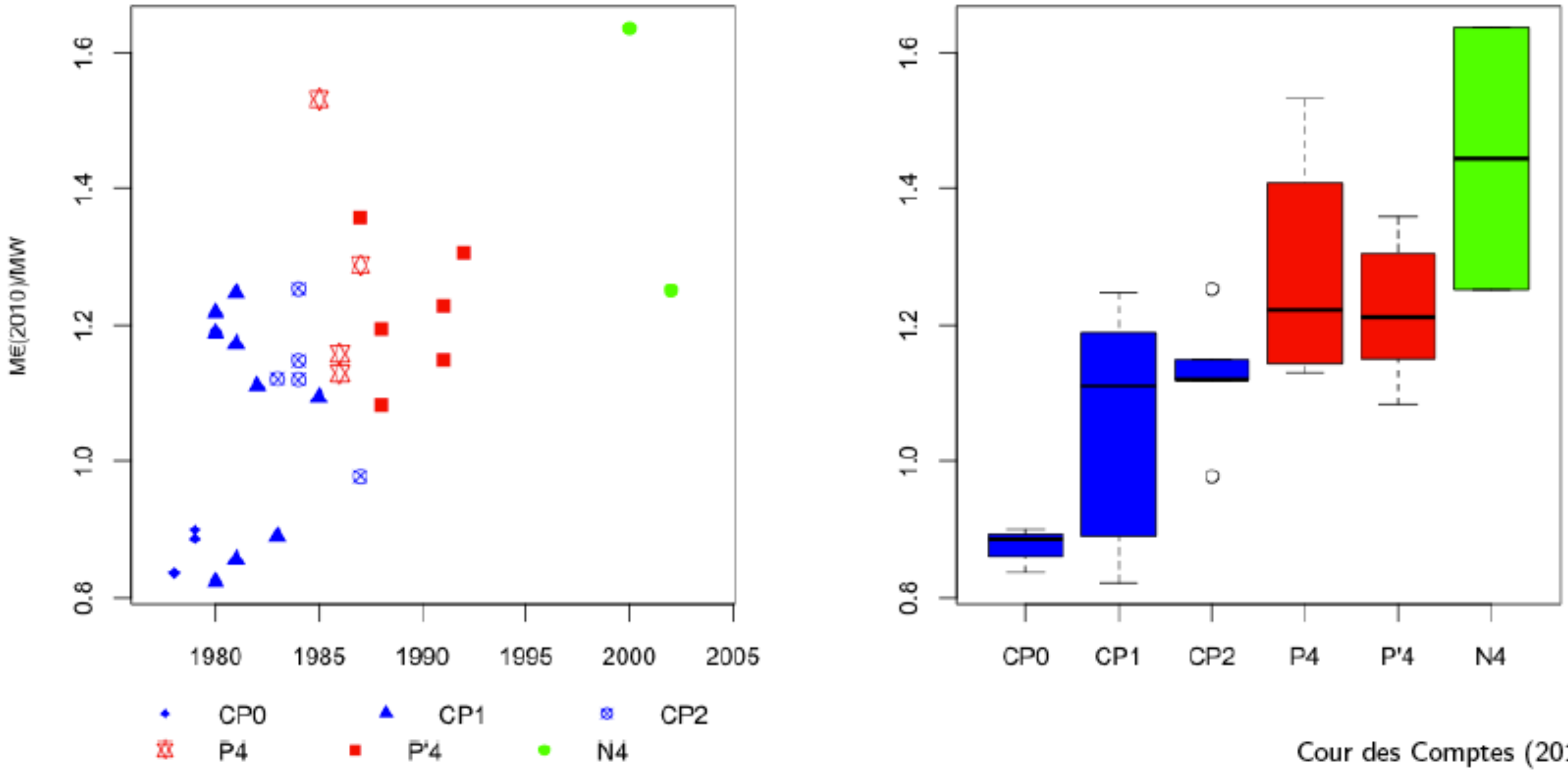
1. The scale effects that were found in some papers were rejected in recent papers, when the effect on the lead-time was taken into account in the cost equation
2. The estimates of learning effects differ substantially across the papers. In the latest ones they were found significant only when the projects were managed by the utilities. There is no evidence to support learning effects at the industry level
3. All the literature has found that the regulatory requirements are one of the main drivers of the cost escalation, even before the Three Mile Island accident

The case of the French nuclear power program

- The French actual nuclear construction costs were recently published (2012)
- The previous assessments were based on estimations like Gruber (2011)
- There is a cost escalation in the French nuclear fleet but it was less that it was estimated and by far lower than the one that the U.S nuclear fleet experienced.



French costs of builds according to the type of reactors



Cour des Comptes (2012)

Main drivers of the nuclear cost escalation in France

- Escobar and Leveque (2012) is the first empirical paper using the actual construction cost of the French nuclear fleet
- The main findings are the following:

1. The scale-up is the main driver of the increase in the costs. Building larger reactors took more time and they turn out to be more expensive
2. The cost of labor is also one important driver of the construction costs, it grew faster than the price index used to homogenize the cost data
3. There is no evidence of learning effects at the industry level. However we found positive learning effects at the palier and type level
4. Safety concerns also took part in the cost escalation. The reactors with better performance in terms of safety indicators were also more expensive

Nuclear construction cost determinants

- Rothwell (1986) proposed a general model of construction cost and leadtimes. Two firms enter in this model: The utility and the Architect-Engineer (A-E)
- The utility determines the optimal construction leadtime as a function of: demand forecast, regulation requirements, discount rate and the relationship between the plant costs and the construction period. Then it requests competitive bids from A-E firms to build the plant
- Within this framework :
  - The utility maximizes the net present value of the value of the nuclear power plant
  - The A-E firm attempts to minimize the cost subject to the leadtime imposed by the utility
- From an empirical point of view, the construction cost will be determined by these two objective functions and will be jointly determined with lead-time, leading to a simultaneity problem and lead-time to enter into the cost equation.
- The inclusion of lead-time in the cost equation can be further motivated by the fact that there exists additional fixed costs associated with longer construction periods, for instance, as utilities are generally in charge of project financing and due to immobilized construction equipment and labor force.

Evidence of the learning effects in U.S and France

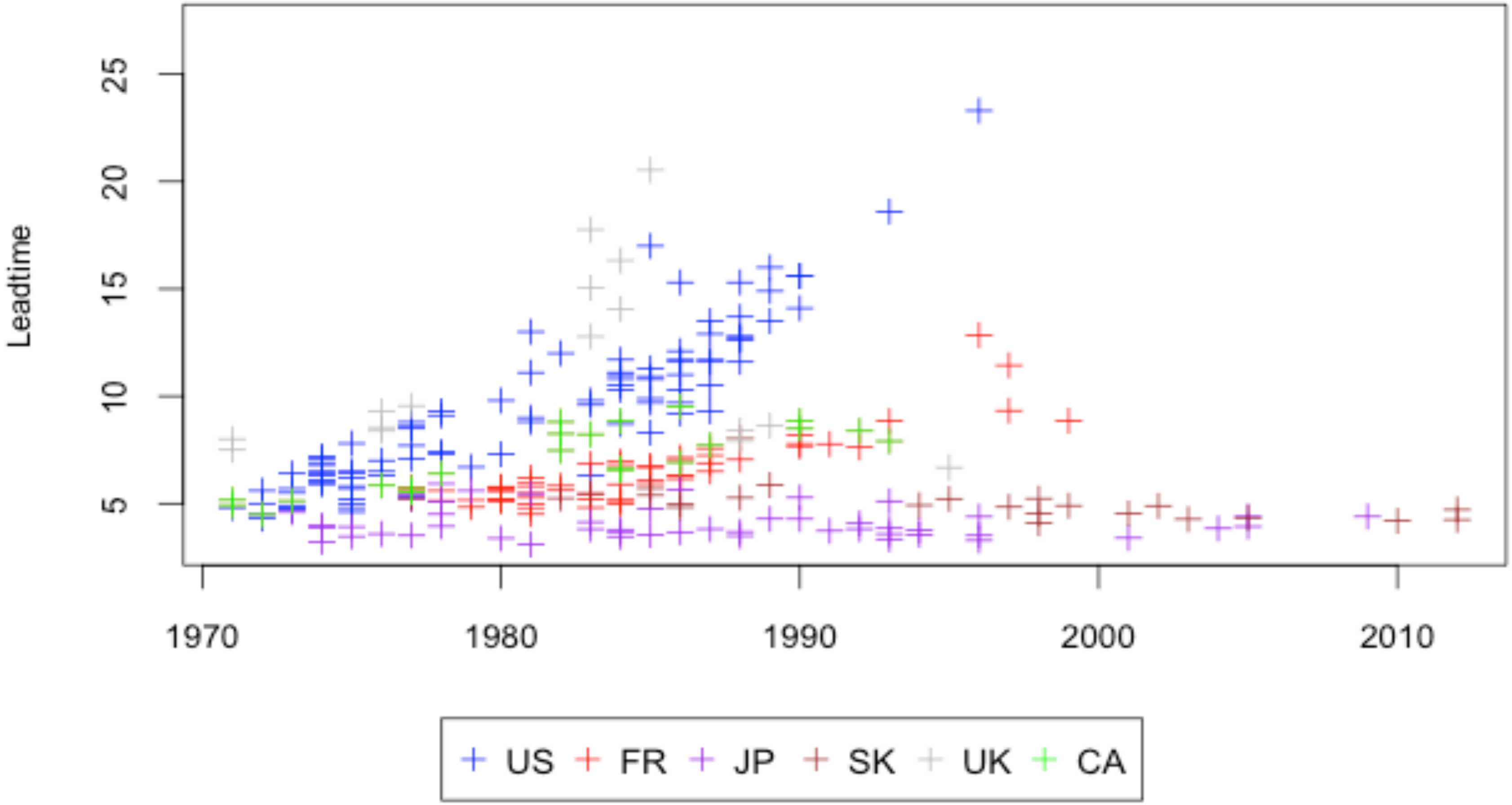
Escobar and Berthélemy (2013) used both U.S and France overnight cost in the model proposed by Rothwell (1986) and later used by Cantor and Hewllet (1986) and estimated this simultaneous system of equations

$$CT_i = \alpha_0 + \alpha_1 LT_i + \sum_{j=2}^{J} \alpha_j X_{i,j} + u_i$$

$$LT_i = \beta_0 + \beta_1 ElecDem_i + \sum_{j=2}^{J} \beta_j X_{i,j} + \varepsilon_i$$

- They used the electricity demand as instrumental variable, given that it affects the leadtime but not directly the construction costs
- They found that the learning effects are conditional to the A-E firm and the technology. This means that cost reductions can be achieved only if the same firm builds repeatedly the same model of reactor
- They results also point out that the less diverse the nuclear fleet, the shorter the leadtimes. This traduces in lower construction costs
- There is evidence of scale effects even when the longer leadtimes are offset in the cost equation

The importance of the construction leadtimes: Evidence for OECD countries



Insights

- Escobar and Berthélemy (2013) found that leadtime is the most important driver of the construction costs
- They also studied the drivers of the leadtimes for OECD countries and the main results are the following:

1. These estimates show that increasing the size of the reactor has a positive and significant effect on lead-time. On average an increase of 3% when scaling up by 10%.
2. The diversity of the nuclear fleet is one of the major differences between countries with longer lead-times and those with shorter construction periods.
3. Is undeniable the negative effect of the two major nuclear accidents on the construction lead-time. Both TMI and Chernobyl were found to be significant structural breaks, showing that these events have an influence beyond borders. As expected, the effect of TMI is stronger on the US compared to other countries.

Conclusion

- There is no *true* cost of nuclear power generation. There are different costs according to the place and time, and the hypotheses made and the methodologies used
- Observed economies of scale and learning effects are small at best
- New data, for instance from China or Korea, could show the contrary
- If nuclear power is unable to escape from the cost escalation curse thanks to standardization, modularization or radical innovation, its competitiveness will erode vis-à-vis other power generation technologies