Les coûts du nucléaires : repères et incertitudes

Séminaire R&D EFESE Macro Energy

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Introduction

- A research program hosted since 2010 at Mines ParisTech and financed by EDF
- Two research axes
  - The analysis of the costs of nuclear stations
  - The governance and regulation of nuclear safety
- Outcomes:
  - One book: *The Economics and Uncertainties of Nuclear Power* (Cambridge U. Press)
  - 5 peer-reviewed papers, 3 on-going working papers, 2 PhD theses
- A website: http://www.cerna.mines-paristech.fr/nuclearpower/

Outline of the presentation

1. A reminder on cost and decision theory
2. Construction costs and the competitiveness of the nuclear industry
   - The cost escalation curse: evidence from OECD countries
   - Learning, scaling and innovation
   - Some policy implications
3. The social cost of nuclear accidents
   - Learning from past catastrophes: a Bayesian revision framework
   - Experts and Public Opinion: Ambiguity-aversion

Cost and decision theory

Social cost private + external costs

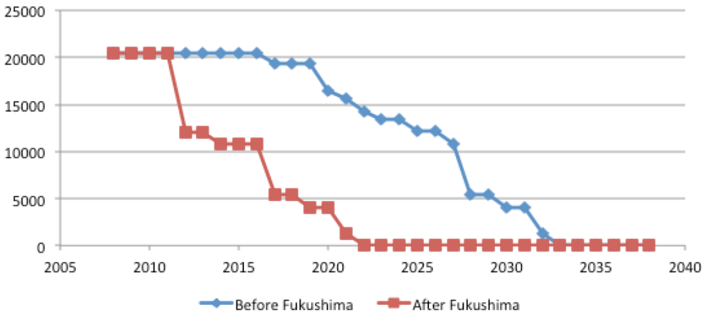
not priced by the market...

Expected cost probability $\times$ cost

not an objective dimension...

- Analogy: cost is more like weight than mass
- The cost to do something rather than the cost of something
- Example: the cost of early phase-outs

The German nuclear phase-out



According to Keppler (2012), the cost of the german decision to accelerate their nuclear phase out is approximately €100 billion

Human behaviour and decision under uncertainty

- Historically, the economic theory of decision has progressed in complexifying the utility function to take observed behaviour into consideration
- Concave utility function to explain risk-aversion (Bernouilli, 1738)
- Allais paradox (1955) can be explained with a weighted utility that is non linear in probabilities: overestimation of low probabilities and underestimation of high probabilities
- Ellsberg paradox (1961) shows that people are averse to ambiguity (i.e., they prefer risk to uncertainties)

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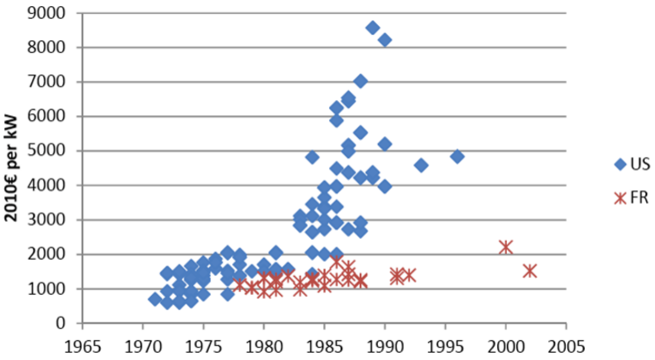
Motivation: Is Nuclear Power Competitive ?

Motivations
- Increasing costs and lead-times
- Existing literature on construction costs of the US fleet
- Few studies and scarce data regarding France or OECD

Two studies
- Lévêque and Rangel (2015)
- Berthélemy and Rangel (2015)

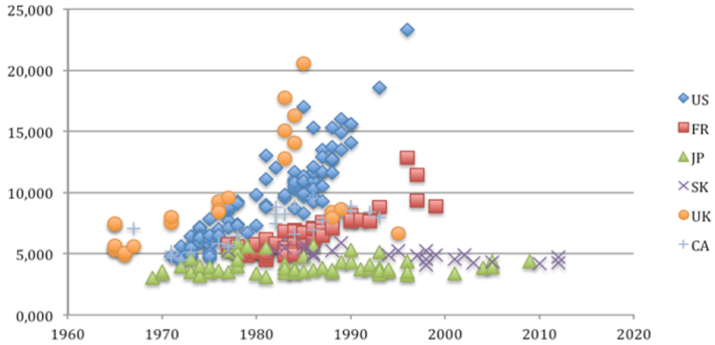
Objectives
- What are the drivers of the cost escalation curse?
- How to enhance the competitiveness of the nuclear industry?

Construction costs in France and in the U.S.



- Observation of escalating costs, even in France (red)

OECD construction lead-times (source: IAEA)



- Observation of escalating lead-times (OECD)

Existing findings

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 doubling 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

- Regulatory requirements are the main driver of cost escalation
- Mixed findings regarding scale effects
- No evidence that supports learning-effects at the industry level

Main findings

What do econometrics tell us?

- Learning-by-doing only occur when the same type of reactor is built by the same firm
- A scale effect: larger reactors are cheaper
- A variety effect: standardization leads to cost reductions

Two studies based on recently available data

- Construction costs in France and in the US
- Lead-times in OECD countries

Disentangling costs and lead-times

A simultaneity issue :

- Lead-times and construction are determined simultaneously by the buyer and seller of a nuclear power station
- Rothwel (1986) proposed a model and a statistical method to account for this bias

Statistical method :

- Two-stage least square method to account for simultaneity
- Use of expected electricity demand as a proxy for lead-times

The learning effect (France)

Rangel and Leveque (2015):

- Positive learning effects occur within constructors and reactor technologies
- On average, the second unit of a reactor built by the same firm would benefit from a 14% construction cost reduction
- There is no evidence for other learning transfers (across technologies or firms)

The scale effect

- Larger reactors are cheaper per MWe
- But they are longer to build, and lead time increases costs
- The net effect remains positive: a 10% increase in capacity reduces the cost by 4.9%

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

The effect of variety

- Homogeneity is measured by a market share index
- Homogeneity of the fleet reduces lead time
- True for France, the US, and OECD data

France and US data

Variable	Cost	Leadtime
In.*Leadtime*	1.064 * (0.622)	
HHI_{mo}	0.374 (0.485)	-0.566 *** (0.160)

OECD data

Variables	(1) (ln *LT*)	(2) (ln *LT*)
$HHI.Mo_i$	-0.291 ** (0.135)	-0.472 *** (0.182)

Other findings

France: Most important drivers of construction cost are lead-times and labour costs

OECD: Fleet diversity is the main difference between countries that exhibit low or high construction periods

Accidents: TMI and Chernobyl have had significant structural consequences on construction lead times.

Innovation: participates to the increase in the costs of construction of nuclear stations

Policy implications

- Future competitiveness of nuclear power will depend on:
  - reduced lead times and overnight costs
  - enhanced standardization and learning effects

- These stakes imply the following trade-offs:
  - standardization vs. innovation: to benefit from standardization without missing out on better and safer new technologies
  - industry concentration vs. market power: to benefit from spillovers

References

Berthélemy, M. and Rangel, L.E. (2015). Nuclear Reactors' Construction Costs: The role of lead-time, standardization and technological progress. *Energy Policy*, 82:118-130

Lévêque, F. and Rangel, L.E. (2015). Revisiting the cost escalation curse of nuclear power generation. *Economics of Energy and Environmental Policy*

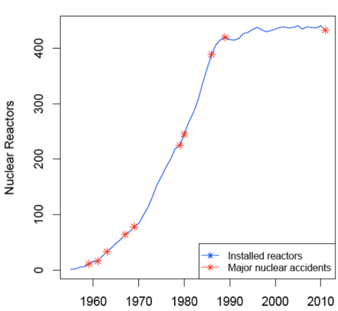
Download: http://www.cerna.mines-paristech.fr/nuclearpower/

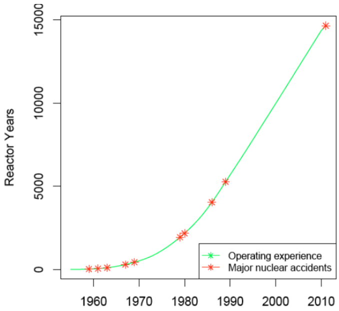
Two research questions

- An applied question:
  - What can be learnt from the Fukushima Dai-Ichi accident regarding the future probabilities of nuclear accidents?
  - Escobar Rangel and Lévêque (2014), *Safety Science*.

- A methodological question:
  - How can we assess the risks of future accidents when information regarding their probabilities or damage is ambiguous?
  - Bizet and Lévêque (2016), Working paper.

Few observations of nuclear power accidents





Question Given the low frequency of nuclear accidents, what information does the Fukushima catastrophe reveal?

Main finding A tenfold increase of the probabilities of accidents to acknowledge the risks of regulatory failures.

No consensus in the measurement of probabilities

In the literature no agreement on the value of the probability

Figure: Existing studies assessing nuclear accident probabilities

Source	Year	Core melts	Large releases	Method
ExternE	1995	5.10^{-5}	1.10^{-5}	PSA
NEA	2003	10^{-5}	10^{-6}	ExternE (PSA)
Hofert, Wuthricht	2011	1.10^{-5}	NS	Poisson law
IRSN	2012	NS	10^{-5}-10^{-6}	IAEA standards
Rabl	2013	NS	10^{-4}	Observed frequencies
IER	2013	NS	10^{-7}	NS
D'Haeseleer	2013	$1,7.10^{-4}$	$1,7.10^{-5}$	Bayesian update
Rangel, Lévêque	2014	$4,4.10^{-5}$	NS	PEWMA model

Interpretation for a 400-reactor fleet

- $p_{PastEvents} = 10^{-4}$: one major accident every 25 years
- $p_{PSA} = 10^{-6}$: one major accident every 2500 years

Accident frequencies are not objective probabilities

The **number of repetitions** does not allow identification :

- 14,500 observed Reactor.Year
- Few observed events
  - Cochran (2011): 12 CMD since 1955
  - Extension to INES > 2: 41 events since 1991

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The **i.i.d. hypothesis** is not respected :

- **Not identically distributed** - Diversity of accident types, of reactor technology or location, of safety regulators...
- **Not independent** - Accidents affect safety standards

What about PSAs?

Estimating probabilities with PSA

- Several PSA codes exist: COSYMA, E3X...
- Calculations based on event-trees
- Designed to pinpoint local safety weaknesses and remedies, not to calculate a single number and its confidence interval

What information do they carry?

- 40 years of nuclear engineering knowledge
- Assuming safety standards are well enforced
- Assuming no unknown unknowns

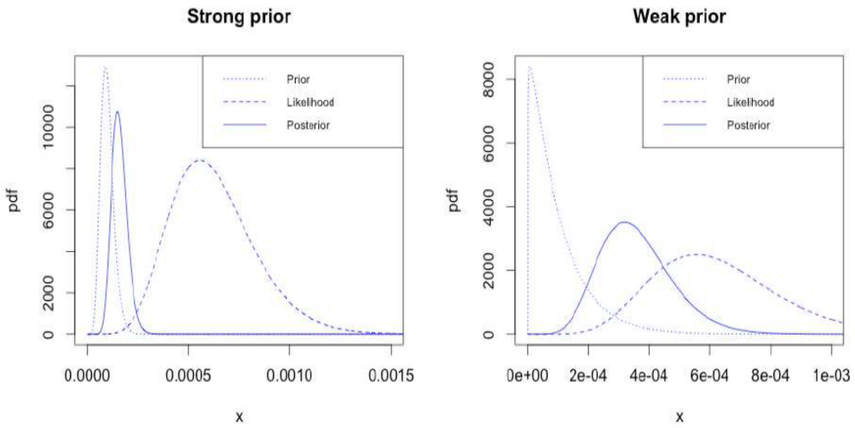
The Bayesian revision framework

- What are the odds of drawing a red ball from an urn, when the n previous draws yielded k red balls ?

- According to Laplace (french mathematician, 1825) : $\frac{k+1}{n+2}$
  - as if two virtual draws yielded one red and one not-red.
- More generally : $\frac{k+st}{n+s}$
  - t: prior regarding the probability of obtaining a red ball, and
  - s: strength of the prior

- For a given problem, s and t can be based on scientific knowledge, or on beliefs

Priors and posteriors



What about nuclear accidents?

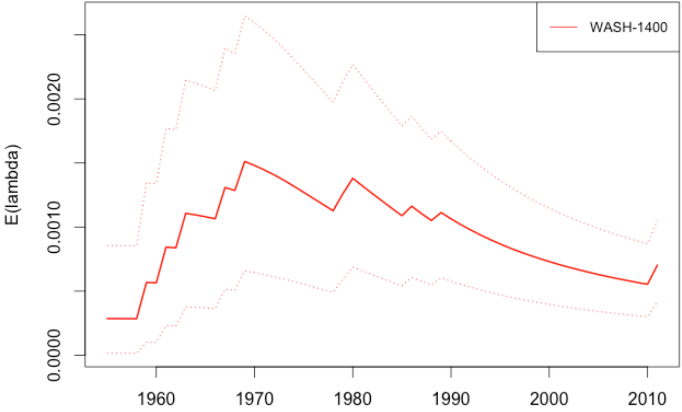
Two contradicting forces

- Increasing safety levels and long periods of time without accidents suggest a decreasing trend in the probabilities of core meltdowns
- Observation of nuclear accidents trigger an upward revision of probabilities to take into account the new pieces of information.

Bayes' rule allows the combination of PSA and observations

1. PSAs are the prior probability of nuclear accidents
2. Each year, the prior is updated, using Bayes rules:
   - if no accident: posterior probability $\leq$ prior probability
   - if accident: posterior probability $\geq$ prior probability

Combining observations and PSAs



Bayesian Poisson Gamma Model, Rangel and Lévêque (Safety Science, 2014).

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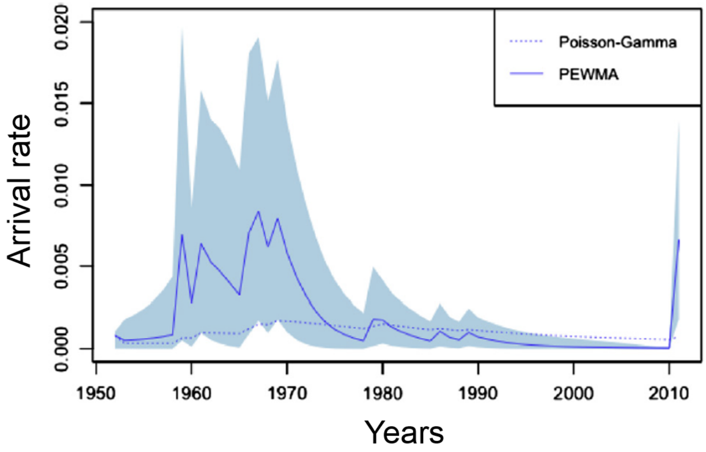

Poisson Exponentially Weighted with Moving Average model, Rangel and Lévêque (Safety Science, 2014).

The post-Fukushima probabilistic update

- Four Poisson models
  - Poisson models usually assume independence
  - PEWMA Model allows to introduce a degree of dependence
- Main results: changes in the expected frequency of nuclear accidents

Summary of results.

Model	$\hat{\lambda}_{2010}$	$\hat{\lambda}_{2011}$	Δ
MLE Poisson	6.175e−04	6.66e−04	0.0790
Bayesian Poisson–Gamma	4.069e−04	4.39e−04	0.0809
Poisson with time trend	9.691e−06	3.20e−05	2.303
PEWMA model	4.420e−05	1.95e−03	43.216

Interpretations

- The risk of nuclear accident has to be significantly revised upward after the Fukushima disaster
- This revision embodies the learnings from the accidents:
  - PSAs assume perfect compliance, which is untrue
  - Competent safety regulators have to be independent, transparent and powerful
- More generally, this revision embodies the idea that upgrading nuclear safety regulators around the world could be a significant source of safety improvements

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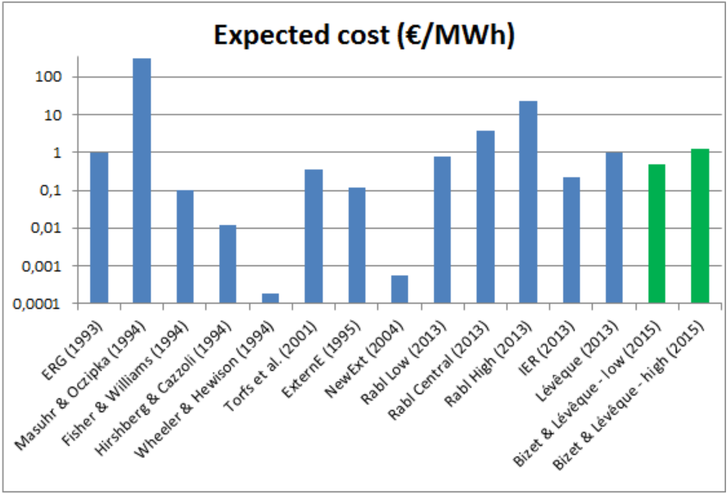
Literature on expected damage

Figure: Existing assessments of the expected cost of nuclear accidents



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- PSAs assume perfect compliance
- Past frequencies are not probabilities

What about public perceptions?

Public perceptions: they should be accounted for

additional costs due to the resentment of policies or technologies

Experimental psychology: distorted perceptions

Rare events are perceived as more likely than they are (Lichtenstein, 1978; Slovic, 1982).

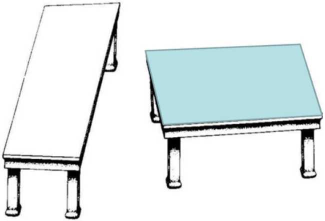
Dreadful events are perceived as more likely than they are (Kahneman, 2011)

Nuclear accidents are both rare and dreadful

Perceived probabilities

- Our perceptions of probabilities are biased (Kahneman, 2011)

- Denominator neglect heuristic: a probability of a 0.0001 loss is perceived lower than a probability of $\frac{1}{10.000}$



Stakes for the decision maker

The sources are conflictual

PSA for a large accident in an EPR: 10^{-7}

Observed frequency of large accidents: 10^{-4}

Perceptions: $> 10^{-4}$?

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Which information should be relied on?

All sources are biased

Using a biased probability could entail:

- wrong level of investments in safety
- wrong timing of phase-outs
- suboptimal technology mixes

How can policy-makers make good decisions in these situations?

Risks and uncertainty (Knight, 1920)

Risk: Various outcomes measured by a probability.
The repetition of the "lottery" confirms the representation.

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Risk: Various outcomes measured by a probability.
The repetition of the "lottery" confirms the representation.

Uncertainty: Various outcomes without attached probabilities.

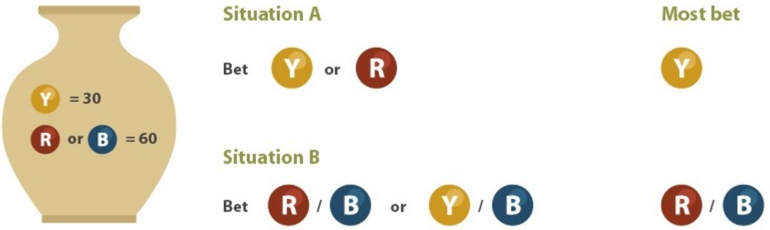
Examples

Risk: roll of dice, roulette wheel...

Uncertainty: Horse races, elections, long-term weather forecasts...

Ambiguity - Ellsberg's paradoxes

Figure: The one-urn Ellsberg paradox



Situation A $\mathbb{P}(Y) > \mathbb{P}(R)$

Situation B $\mathbb{P}(Y \cup B) < \mathbb{P}(R \cup B)$

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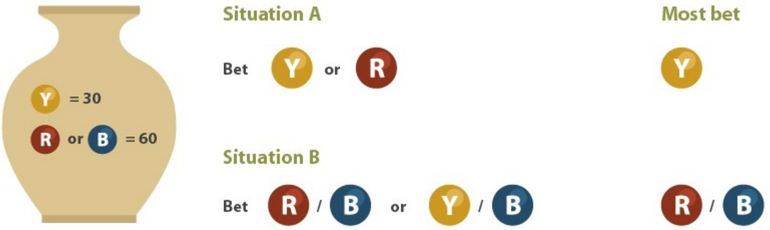

- People prefer bets described by known probabilities
- Ambiguity-aversion is not accounted for in classical cost-benefit analysis

Nuclear accidents are uncertain events

Ambiguous information on probabilities

- Observed frequencies are not probabilities
- People's perceptions are biased
- Experts' calculations are imperfect

How can we overcome this uncertainty?

A new assessment method

- We apply a decision criterion (Ghirardato et al, 2004)
- Uncertainty is represented by **several probabilities** describing the rare disaster

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Adaptation to the calculation of the expected cost

$$\mathbb{E}_{\alpha} C = \alpha \mathbb{E}_{\textit{worst case}}[C] + (1 - \alpha)\, \mathbb{E}_{\textit{best case}}[C]$$

The decision rule (1/2)

- We apply a decision criterion (GMM, 2004)
- Decision Maker is assumed to behave according to six axioms:

Ghirardato's "rationality" (2004)

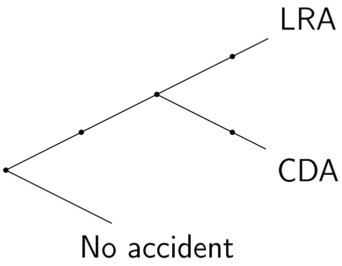
- **GMM1:** Transitive Weak-order (usual)
- **GMM2:** Certainty Independence (new)
- **GMM3:** Continuity (technical, usual)
- **GMM4:** Monotonicity (usual)
- **GMM5:** Non-degeneracy (trivial)
- **GMM6:** Certainty-equivalence (new, technical)

Underlying structure

Two categories of accidents

- Core Damage Accident without releases (CDA)
- Large-Release Accident (LRA)

Figure: A simplified event-tree structure for nuclear accidents



Hypotheses concerning nuclear accidents

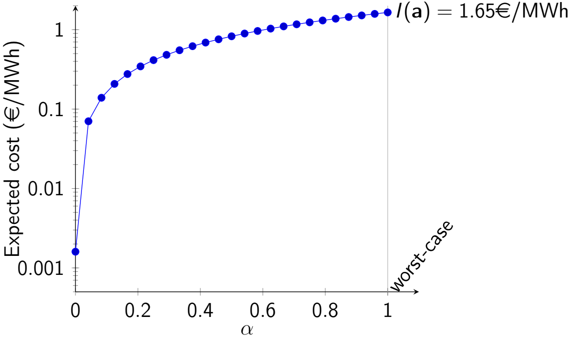
Table: Hypotheses regarding damage and probabilities

	damage (10^9€)	best-case probability	worst-case probability
core-damage	2, 6	10^{-6}	10^{-3}
large-release	180	10^{-7}	10^{-4}

Sources Damage: Sovacool (2008) and IRSN (2013)
Probabilities: AREVA and past events

The expected cost of nuclear accidents

Figure: Expected cost in €/MWh as a function of α



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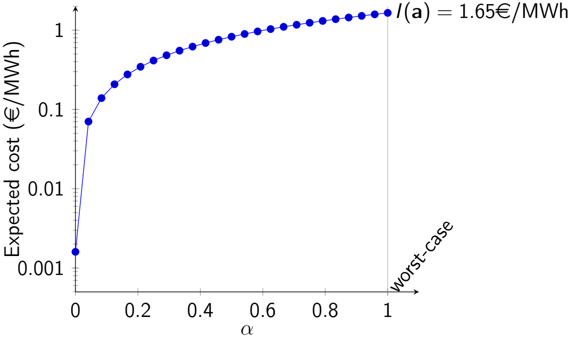

- worst case scenario - 1.7€$/MWh$
- worst scenario with macro consequences 7€$/MWh$

Policy implications

Perception The expected cost of nuclear accidents ought to reflect public perceptions as well as technical investigations

Policy The cost found in this study is small when compared to the LCOE of nuclear power new builds

Method Other uses to assess the cost of other rare disasters (oil spills, dam failures, nuclear safety standards or accident mitigation plans...)

Thank you for your attention !

More information and references :

- www.cerna.mines-paristech.fr/leveque/
- www.cerna.mines-paristech.fr/bizet/
- www.cerna.mines-paristech.fr/nuclearpower/

References