Synthesis on the Economics of Nuclear Energy

Seminar on Energy Economics
Dauphine, Mines, PSL

Paris, September 18, 2014

William D'haeseleer

Synthesis on the Economics of Nuclear Energy

Study for the European Commission, DG Energy

Final Report

November 27, 2013

William D. D'haeseleer

Professor at the University of Leuven (KU Leuven), Belgium

Table of Contents

Table of Contents

Objective / Scope

Establish an exhaustive picture of cost estimates in the nuclear sector [...] on the basis of the available up-dated information

[present in the 'open' literature]

[and cross checked by actors from industry]

Concentrate on reactors to be built in EU

Objective / Scope

- Widely varrying estimates/quotations in the literature
  - Optimistic/rosy by nuclear advocates
  - Pessimistic/exaggerated by critics
- Only makes sense to obtain **range** or **order of magnitude**
- Quote from Engr Company Black & Veatch (USA):

> Given all these sources of variability, contractors normally speak in terms of cost ranges and not specific values. Modelers, on the other hand, often find it easier to deal with single point estimates. While modelers often conveniently think of one price, competition can result in many price/cost options. It is not possible to estimate costs with as much precision as many think it is possible to do; further, the idea of a national average cost that can be applied universally is actually problematic. One can calculate a historical national average cost for anything, but predicting a future national average cost with some certainty for a developing technology and geographically diverse markets that are evolving is far from straightforward.

Objective / Scope

Our goal:

- obtain **'average' estimate** for **generic case**
  - Adjust for **differences**:
    - Brownfield / greenfield
    - Single / twin
    - FOAK / NOAK / Fleet
  - Assuming reasonable range of **provision for contingencies**:
    - Depending on the state of the estimate (concept, bidding,...)
  - With reasonable **range for uncertainty/accuracy**

Objective / Scope

- Our obtained **'average' estimate** for **order of magnitude** is **NOT** based on a *representative* sample of data on which sophisticated statistical or econometric analyses should/can be performed!
- The data are **scan** of "resonable", published results with varying degree of quality, detail, specification, circumstances,...
- Some strange outliers or obvious "wet-finger" approaches are rejected
- Propsed 'average' estimate only served to **provoke reaction from nuclear-market conoisseurs!**

Table of Contents

Table of Contents

Purely illustrative chapter!

Context & Setting the Scene

- **Cost** depends on viewpoint *investor* (e.g., discount rate), on *geographical* aspects, on *time* of estimate, …
- Actually should consider the *opportunity cost* – but then necessary to compare to other elec prod means → out of scope of this study
- Concentrate on "engineering-economics approach" or "cost accounting approach" for private cost
- But **social cost = private cost + external cost**

Context & Setting the Scene

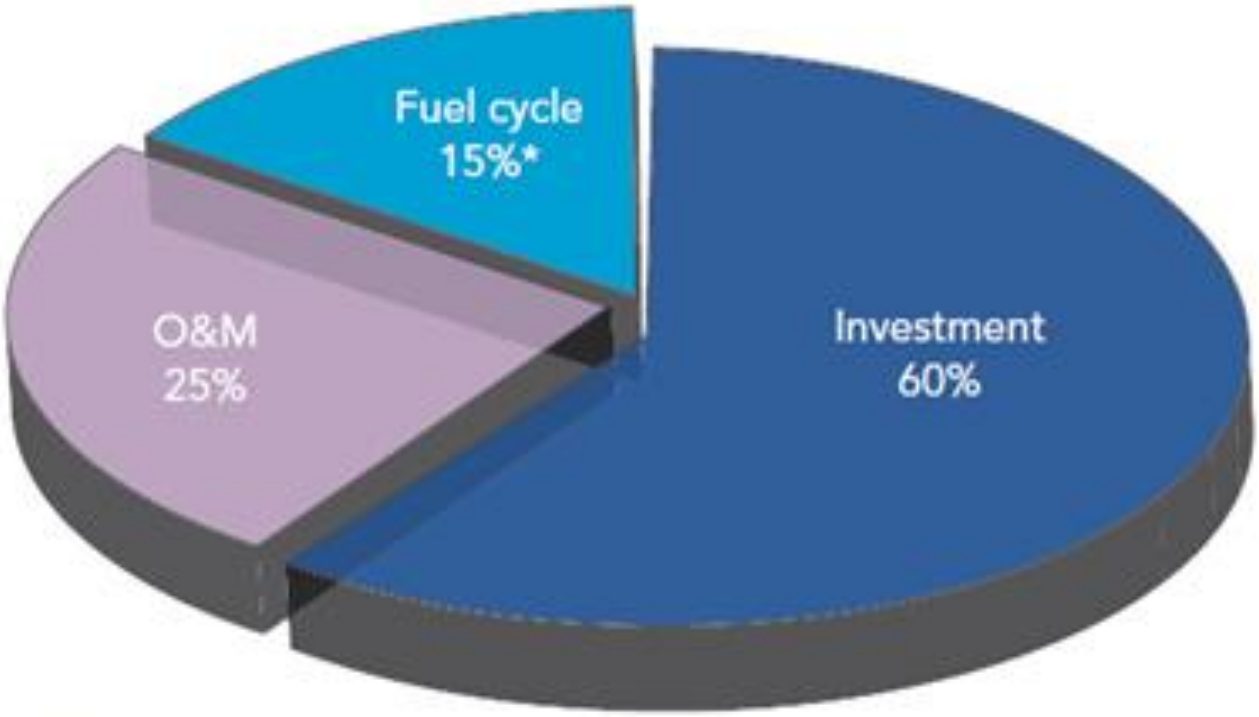
Cost Elements of Nuclear Generation

Private costs / Resource costs

- Investment cost
- Decommissioning cost
- Operation & Maintenance (O&M cost)
- Fuel cycle (including the back end) cost

Context & Setting the Scene

Cost Elements of Nuclear Generation



* The cost of natural uranium typically represents only 5%.
Source: NEA and IEA (2005).

Context & Setting the Scene

Cost Elements of Nuclear Generation

- Capital is clearly dominant: **~ 60-85%**
- O&M **~ 10-25%**
- Fuel Cycle **~ 7-15%**

Note: ‘fuel cycle’ includes both upstream & downstream parts

Context & Setting the Scene

Cost Elements of Nuclear Generation

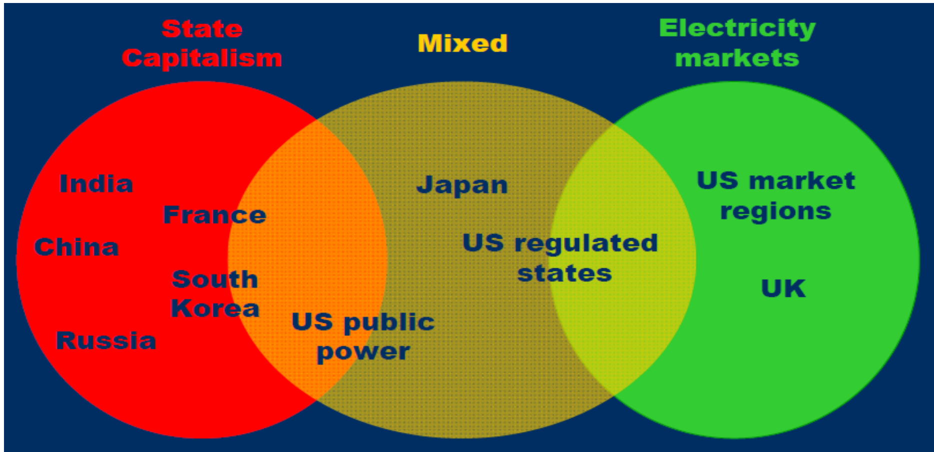
- **<u>remaining externalities</u>**
  - Radioactive emissions
  - Long-term waste disposal (sometimes part of fuel cycle; often already internalized)
  - Accidents – liability
  - Proliferation
  - Avoided CO_2 emissions – a positive externality? (Also the small amount of embedded CO_2 is to be considered)
  - System effects
    - Negative compared to gas & coal: ‘less well’ dispatchable (load following)
    - Positive with respect to wind and sun / nuclear *is* dispatchable to some extent and the need for large rotating inertia

Context & Setting the Scene

- Public versus private investors
- Regulated versus liberalized market

→ *determination of the cost of capital*

- Debt fraction (and interest rate)
- Equity fraction (and rate of return investors)
- Hence the **WACC**



Context & Setting the Scene

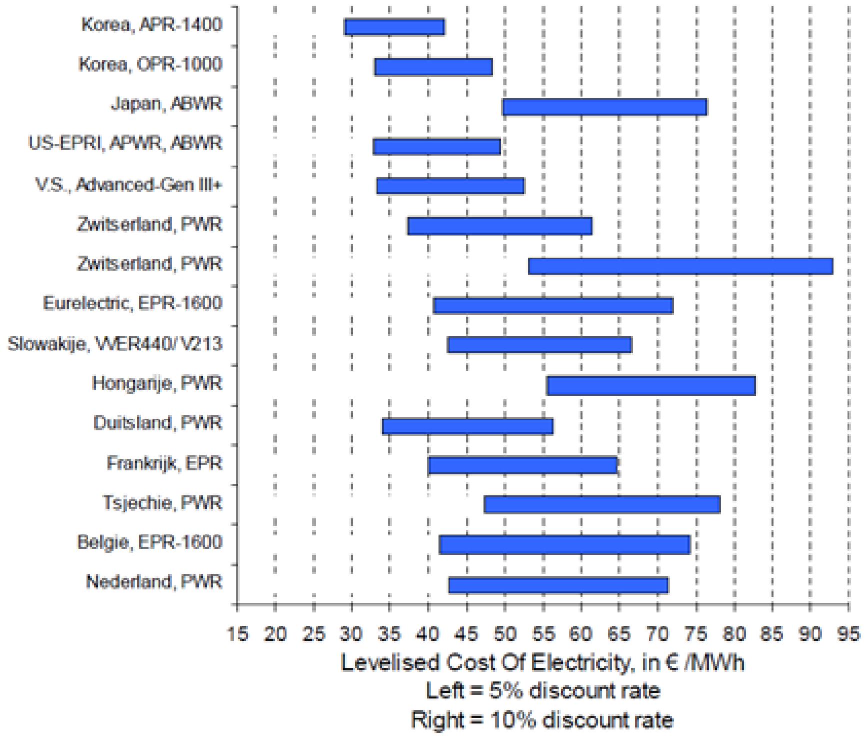
Levelized Cost of Electricity (LCOE)

LCOE determined by set of *contextual parameters*

- Cost elements of LCOE (Capex, Opex, Fuel)
- Large geographical/ regional variety
- Influencing factors: capacity factor, discount rate, construction period (IDC)
- Unimportant factors: lifetime (beyond 40y)
- Decommissioning is actually negligible

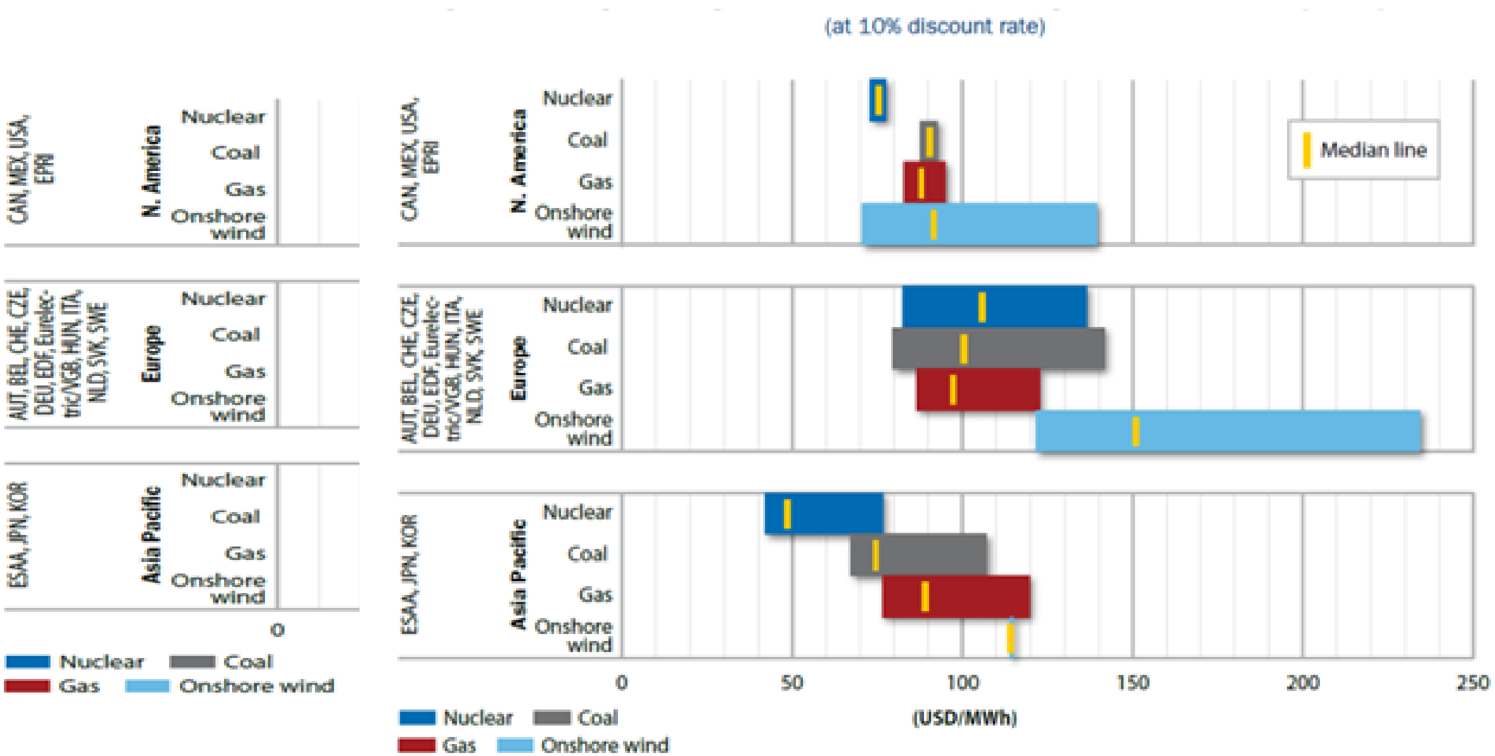
Context & Setting the Scene

Variation of Levelized Cost of Electricity (LCOE)

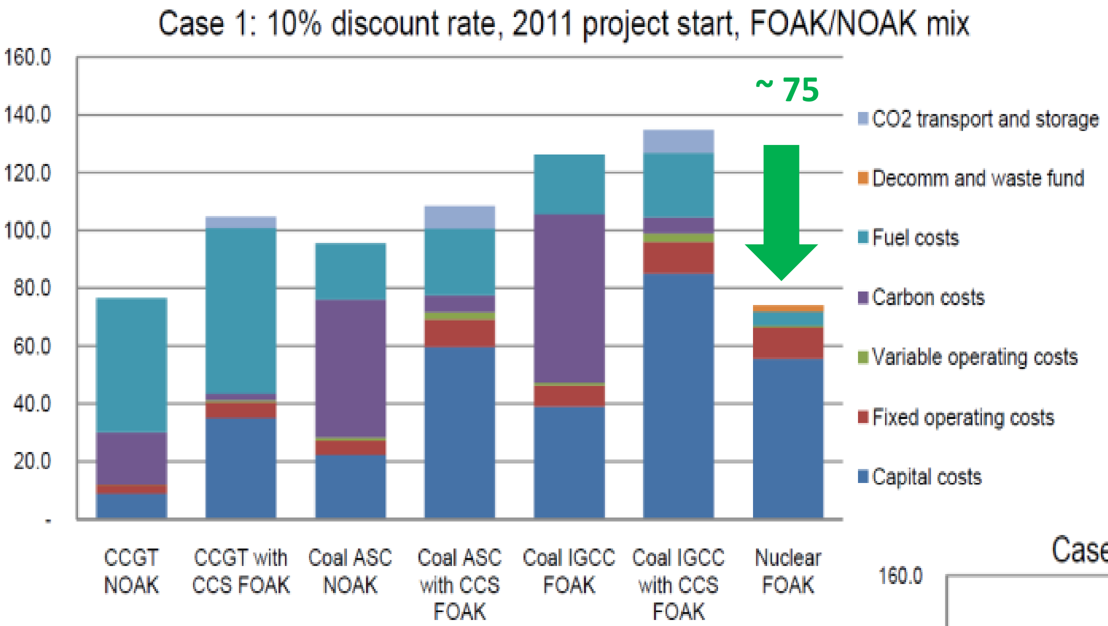


Context & Setting the Scene

Variation of Levelized Cost of Electricity (LCOE)



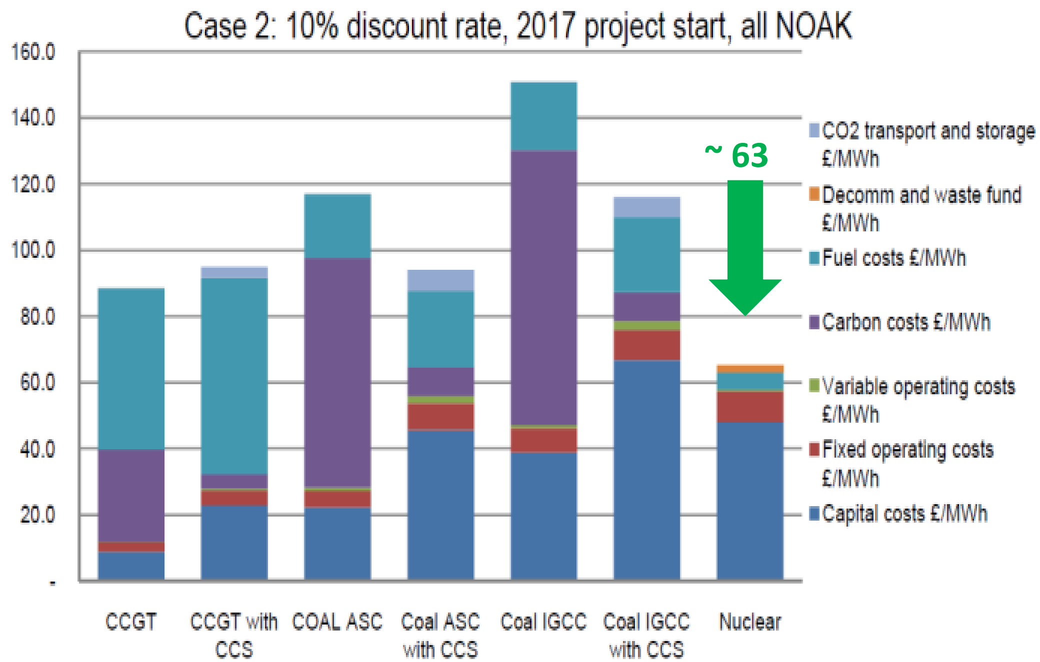
LCOE - Illustrations



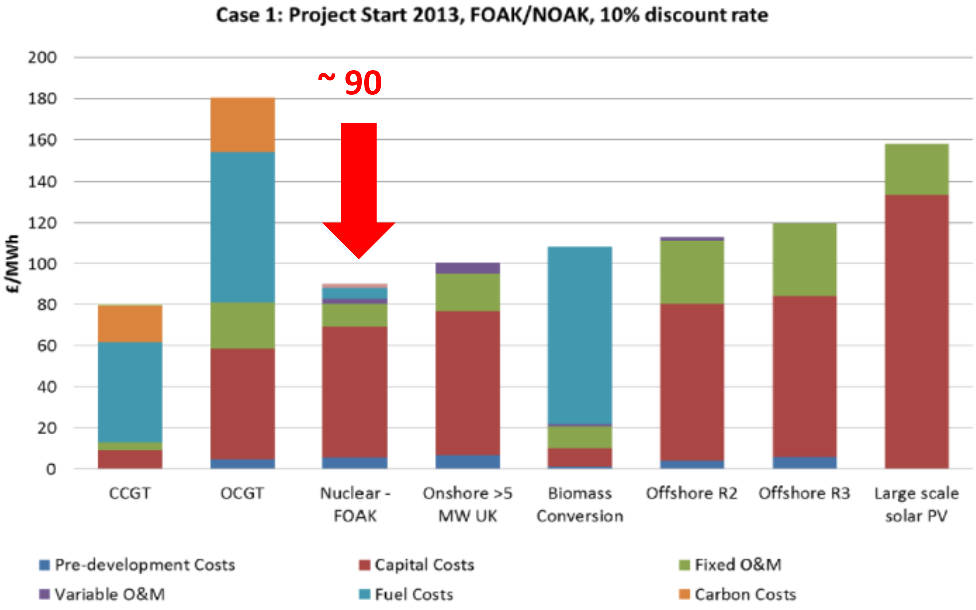
UK Figures

Parsons & Brinckerhoff **2011**

GBP$_{2010}$/MWh



LCOE - Illustrations



UK Figures

Parsons & Brinckerhoff **2013**

GBP$_{2012}$/MWh

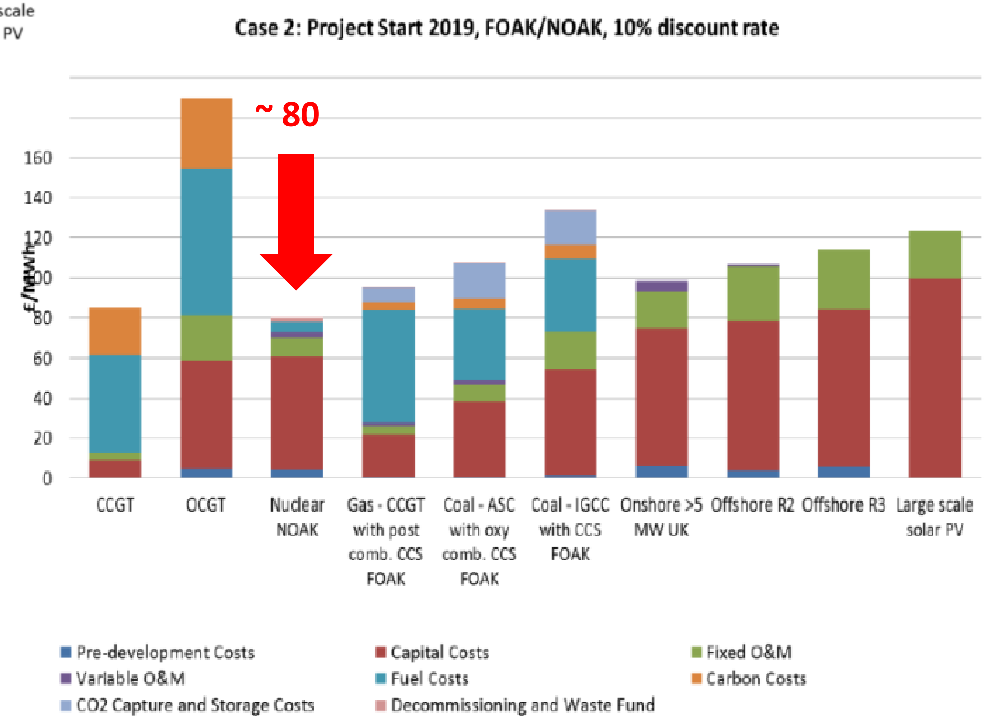


Table of Contents

Table of Contents

Crucial Chapter!

Table of Contents

Definitions, Conventions …

PWR –BWR Generic Estimate

- Gen III projects in Europe: (light) water cooled reactors.
- No distinction between PWR and BWR; a generic type of reactor is considered

The considered reactors must satisfy the European Utility Requirements (EUR):

- EPR – *"European Pressurized Reactor"*
- AP1000 – *"Advanced Pressurized Reactor"*
- ABWR – *"Advanced Boiling Water Reactor"*
- VVER – *"Vodo-Vodyanoi Energetichesky Reactor"*

- Korean OPR and APR reactors not considered since no EUR accreditation

Table of Contents

Definitions, Conventions …

Fuel Cycle: Upstream /Downstream – Decommissioning

- "A priori" estimate entire fuel cycle ~ 7 – 15% of LCOE
- 'Fuel cycle' = upstream + back end

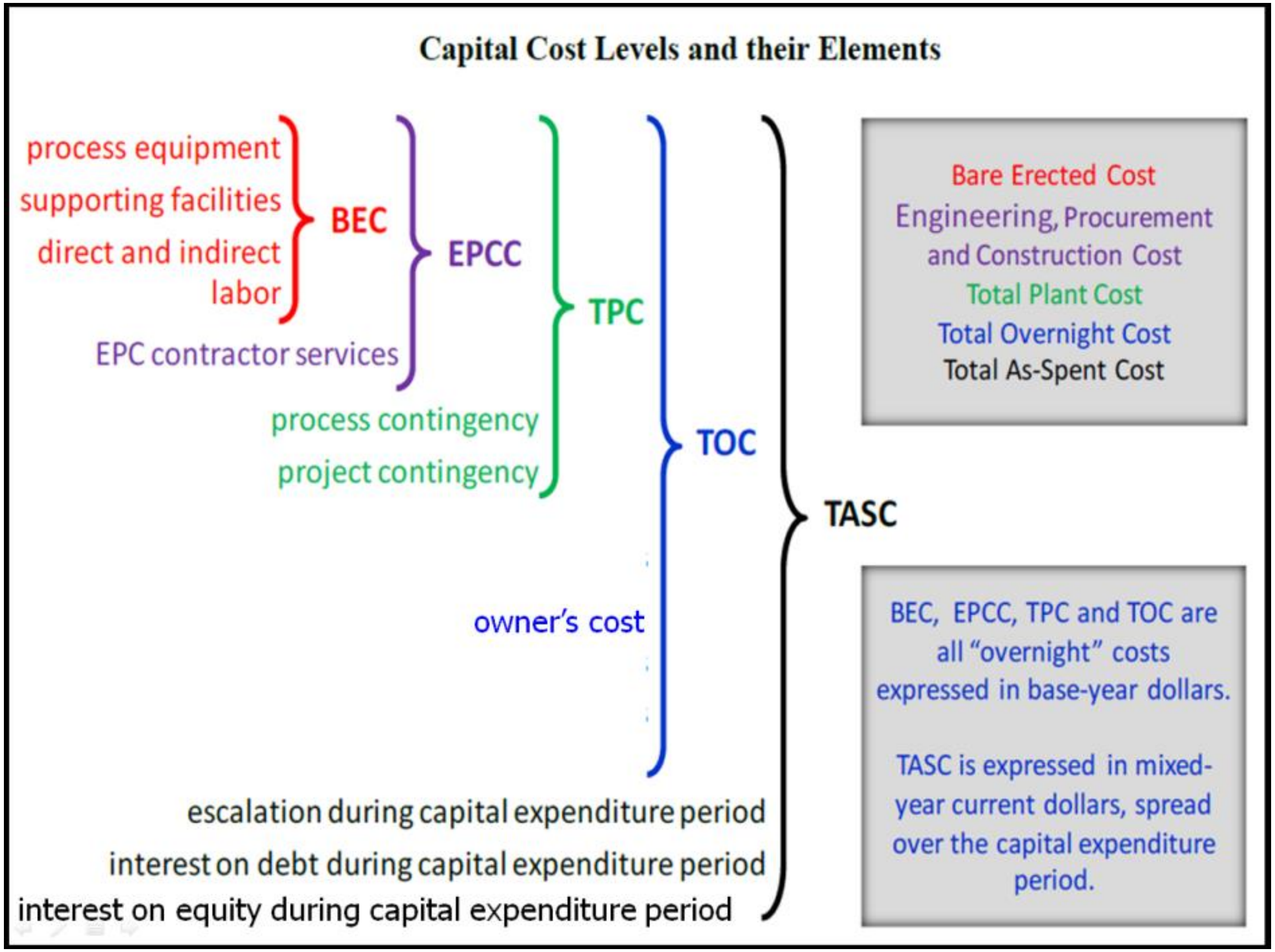
- In UK upstream/downstream separated
  - Fuel cost (upstream) ~ 11% of LCOE
  - Back-end cost ~ 3% of LCOE
  - Hence BE/(BE+Upstr) = 3/14 ~ 21% → BE ~20 of fuel-cycle cost
- In USA statutory fee of 1 $/MWh for disposal spent fuel

To be confirmed later

Table of Contents

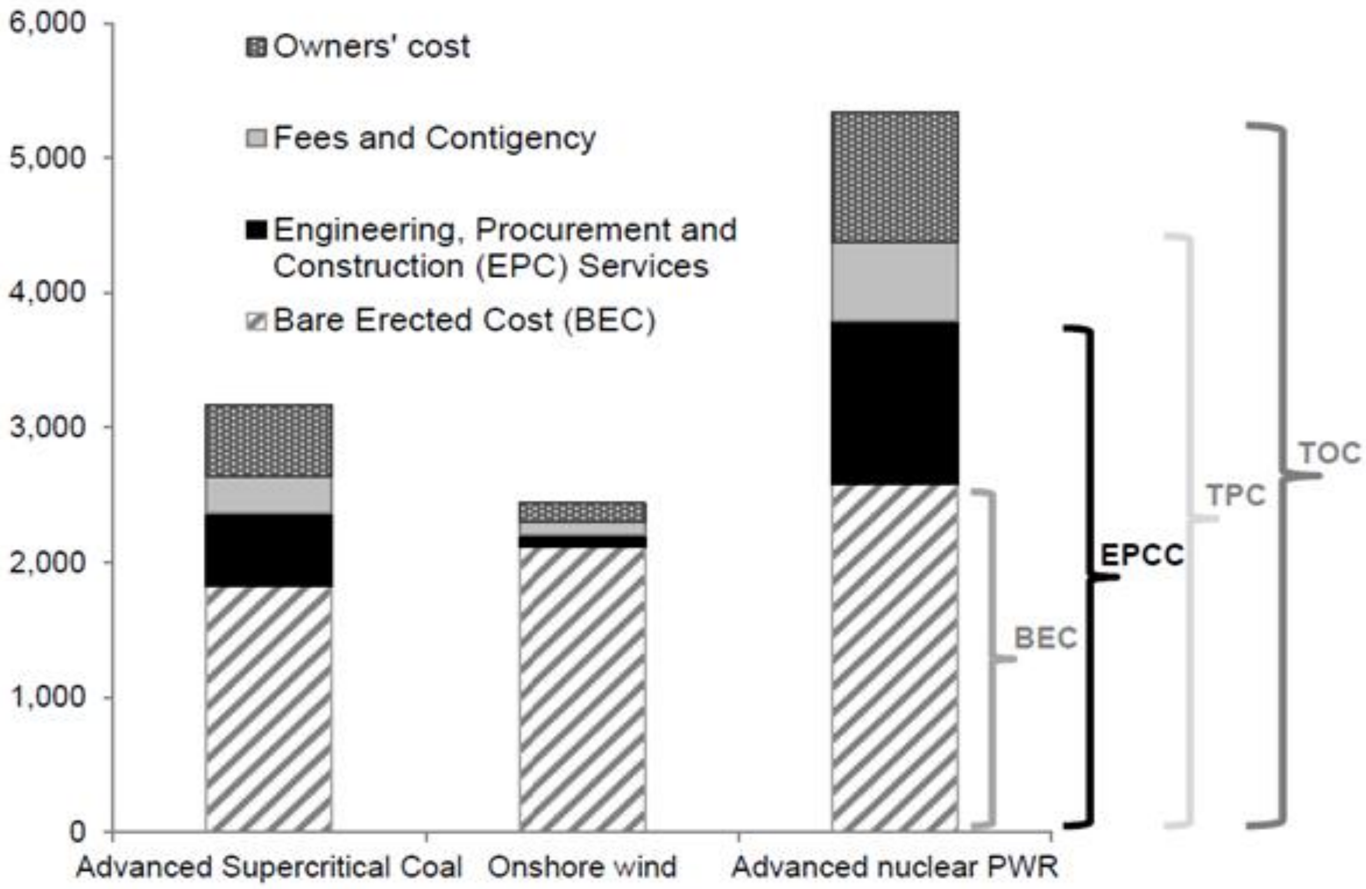
Definitions, Conventions …

Investment Cost – Definition



Definitions, Conventions …

Investment Cost – Definition



Definitions, Conventions …

Investment Cost – Definition

Owner's Cost

- Not unique definition in the literature
- We exclude costs outside fence from owner's cost

  - **~ 15-20% of the EPCC** [MIT, 2003, 2009][Parsons, 2009a][Rothwell, 2010] ; or,
  - **~ 15-20% of the TPC** [NETL, 2012]; or,
  - **~ 15-20% of the OCC** [UChicago, 2011] Actually EPCC is called 'Base Overnight Construction Cost' by [Rothwell, 2010]

Definitions, Conventions …

Importance of **Interest During Construction (IDC)**

- Following Du & Parsons (2009):

IDC = **15%** of the 'total cost' (both) expressed in USD_{2013}

IDC = **17.7%** of the 'overnight construction cost' (both) expressed in USD_{2013}

IDC = **19.4%** of the 'construction cost as expended' during construction in nominal/mixed USD, *including capital charges*;

IDC = **24%** of the' total construction cost as expended' during construction in nominal/mixed USD, but *without capital charges*.

Nominal discount rate = 11.5%

Inflation = 3%/a

Construction period = 5 years

Table of Contents

Definitions, Conventions …

LCOE – Computational Guidelines

Use expressions by NEA/IEA 2010 for New build and LTO:

Example for new build:

$$\Sigma_t (Electricity_t * P_{Electricity} * (1+r)^{-t}) =$$
$$\Sigma_t ((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) \quad (1).$$

From (1) follows that

$$P_{Electricity} =$$
$$\Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t(Electricity_t*(1+r)^{-t})) \quad (2),$$

which is, of course, equivalent to

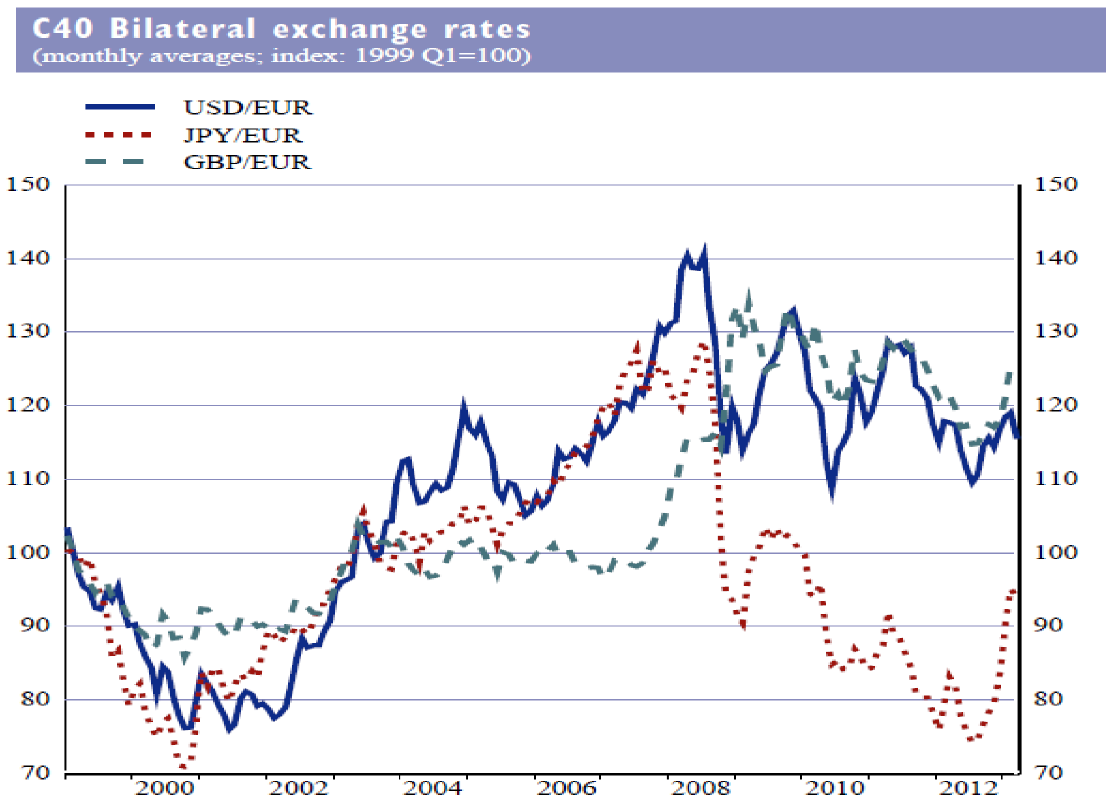
$$LCOE = P_{Electricity} =$$
$$\Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t(Electricity_t*(1+r)^{-t})) \quad (2)'.$$

Table of Contents

Definitions, Conventions …

Exchange Rates

Use Market Exchange Rates (MER):



Used methodology if using foreign values, then:

1) **Escalation (inflation and other) are done in foreign currency up to 2012**
2) **Then in 2012 conversion to EUR2012 is done**

Table of Contents

Table of Contents

Definitions, Conventions …

Inflation – Escalation

Three sorts of escalation:

Esc1 = usual inflation via GDP Deflator, CPI, PPI

Esc2 = actual nominal price evolution of power plants

Esc3 = anticipated cost escalation during construction,
extrapolated from historic data

Definitions, Conventions …

Inflation – Escalation

<u>Must be careful with double counting !</u>

If **Esc2** is used, then **Esc1** no longer needed!

some references are unclear and/or do double counting

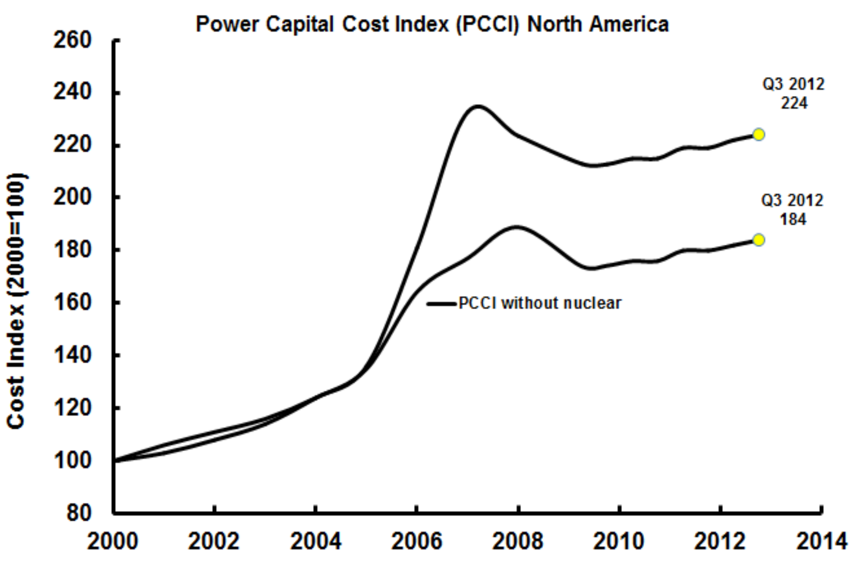
Esc3 is ***NOT*** accepted in this work as pure “speculation”

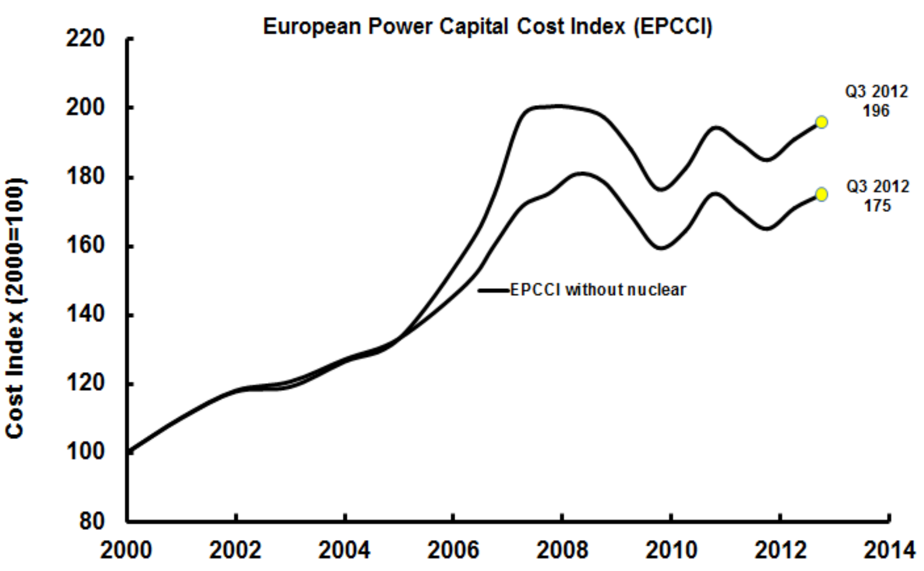
→we will define cost <u>ranges of uncertainties</u>, taking into account FOAK/NOAK/fleet effects

Definitions, Conventions …

Inflation – Escalation

Historic estimate of cost escalation of Power Plants **Esc2**



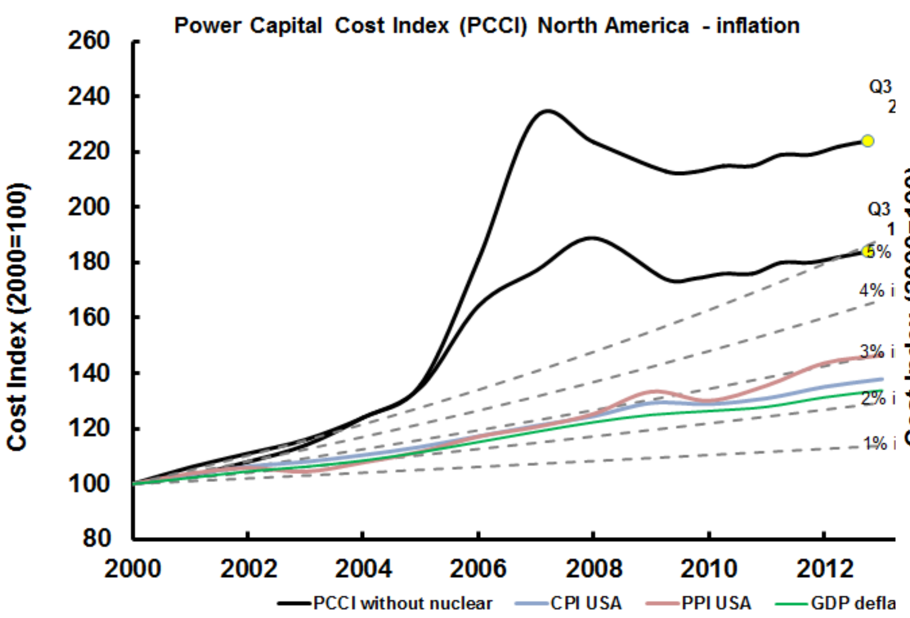


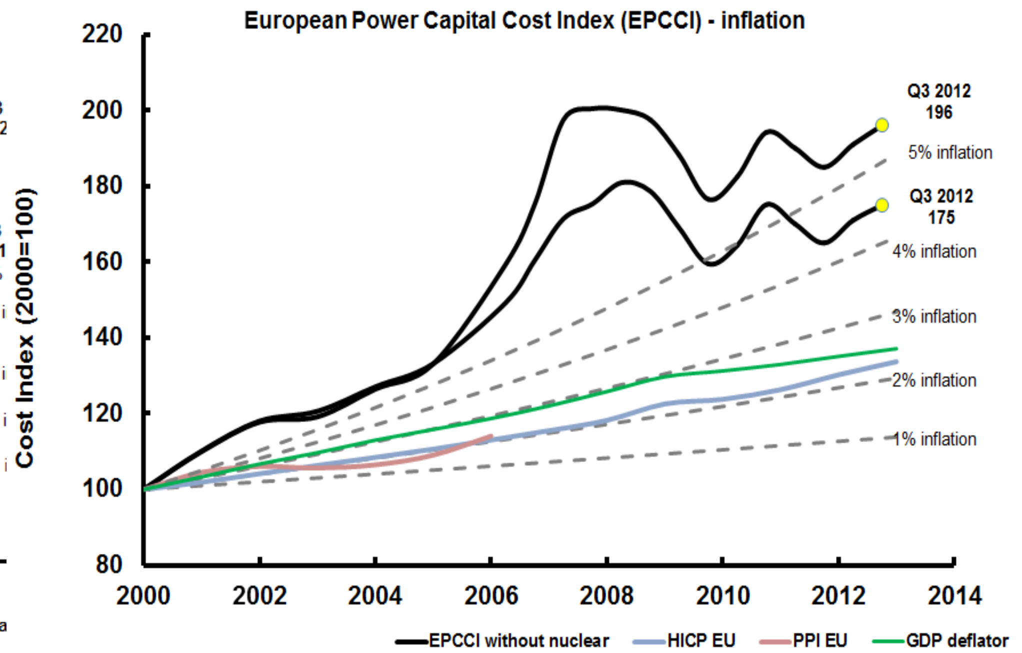
IHS CERA Power Capital Cost Indices (Esc2)

Definitions, Conventions …

Inflation – Escalation

Historic estimate of cost escalation of Power Plants **Esc2**





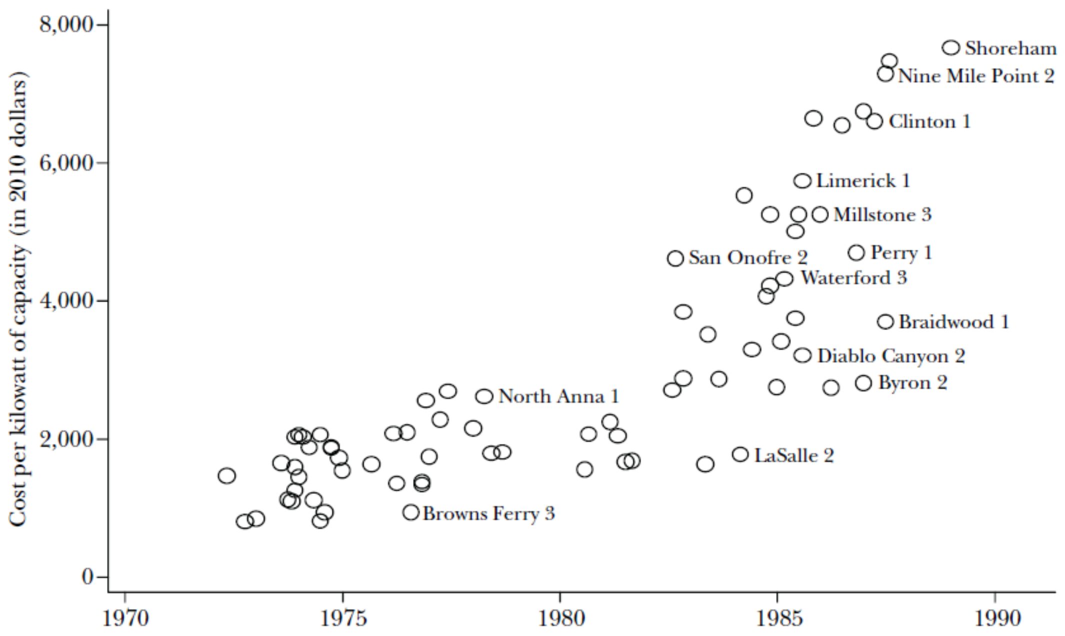
IHS CERA Power Capital Cost Indices (Esc2) compared to usual inflation (Esc1)

Table of Contents

Definitions, Conventions …

Inflation – Escalation

Historic cost escalation of the real construction costs of NPPs – **USA**

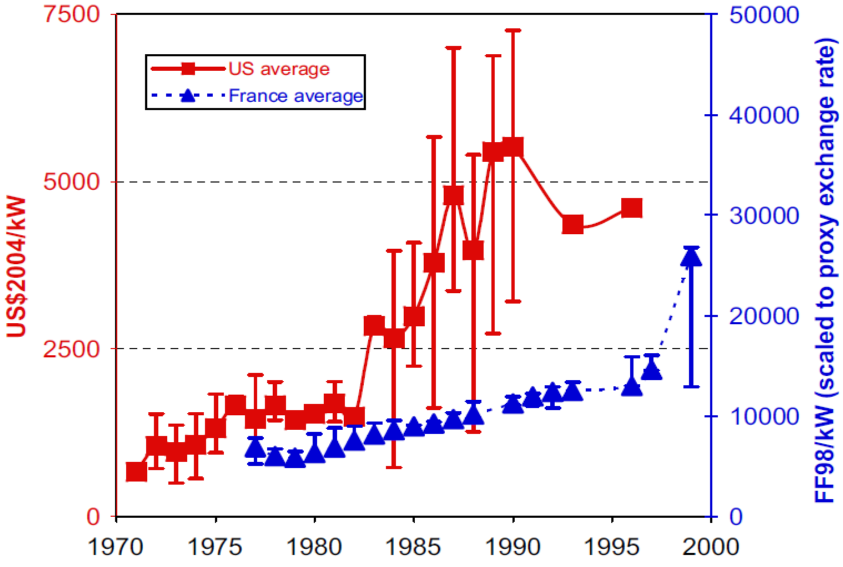


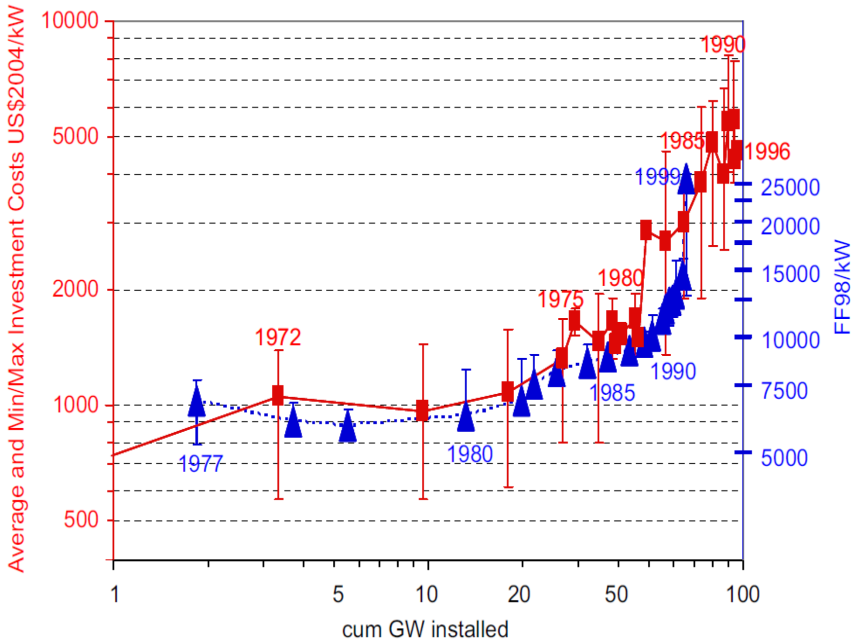
Source: U.S. DOE (1986), table 4.
Notes: Figure 3 plots "overnight" construction costs for selected U.S. nuclear power plants from the U.S. Department of Energy (1986). The figure includes *predicted* costs from the same source for a handful of reactors that were under construction but not yet in operation in 1986.

Definitions, Conventions …

Inflation – Escalation

Historic cost escalation of the <u>real construction</u> costs of NPPs – **FR**





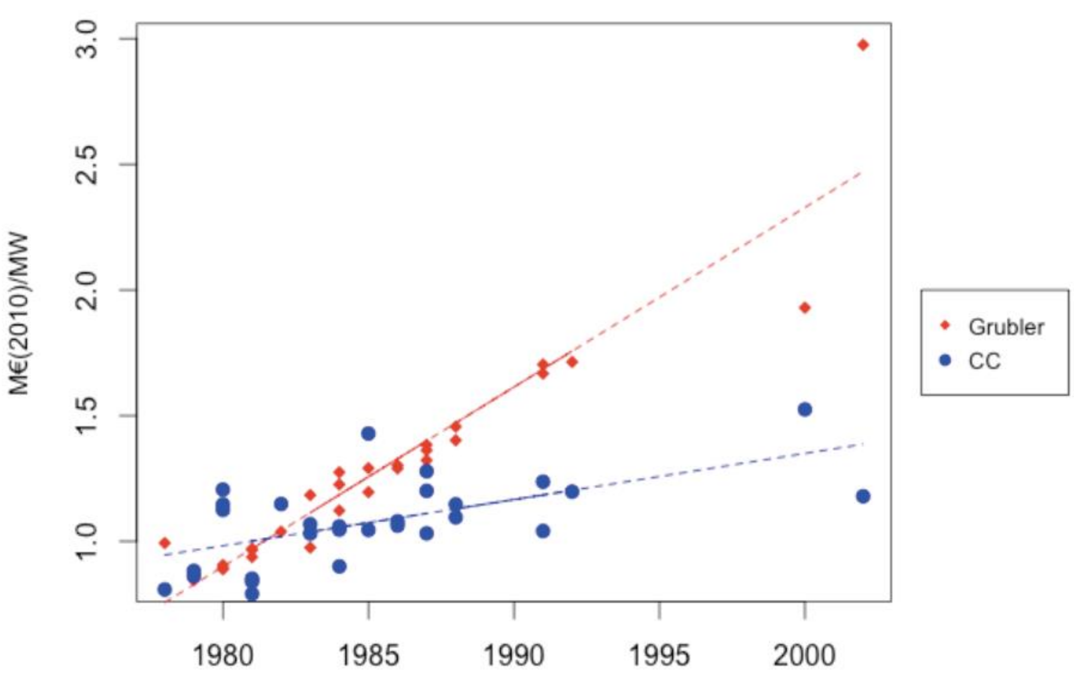
Grubler, Energy Policy 2010

Definitions, Conventions …

Inflation – Escalation

Historic cost escalation of the <u>real construction </u>costs of NPPs – **FR**

Enter Lévêque, 2012, who uses the “*right*” numbers from the CdC



Escalation Grubler: 9%/a

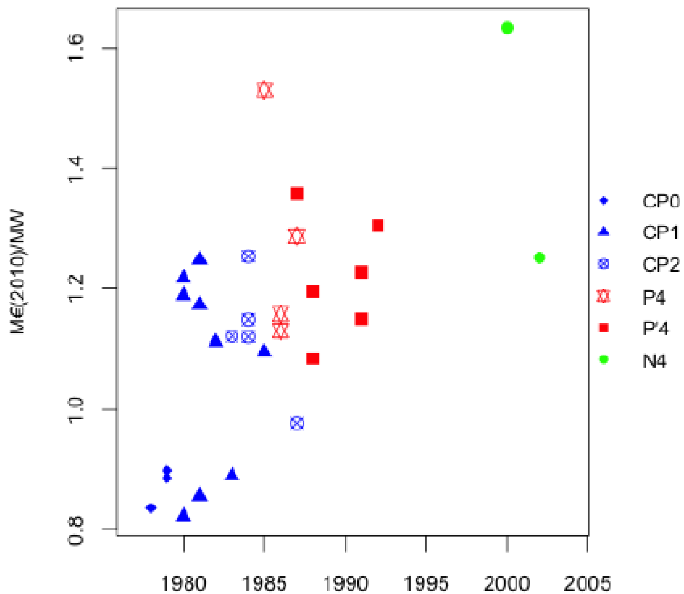
Escalation Lévêque: 3.8%/a

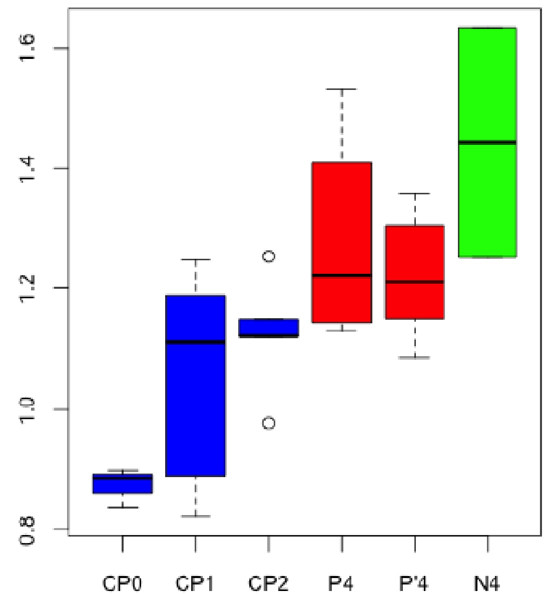
Definitions, Conventions …

Inflation – Escalation

Historic cost escalation of the <u>real construction </u>costs of NPPs – **FR**

Lévêque, considers the different 'paliers' and 'types'





Definitions, Conventions …

Inflation – Escalation

Historic cost escalation of the real construction costs of NPPs – FR

Lévêque, through careful econometric analysis:

- No scale effect. Bigger size of reactors did not lead to lower costs / kW. Larger reactors more complex →longer lead times and greater risk of cost overruns.
- Correlation between capacity, lead time and cumulative experience explained as follows: so-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.
- Cumulated experience of the industry did not induce cost reduction: a consequence of an alleged intrinsic characteristic of nuclear reactor construction: lumpy investments and site-specific.
- But, there is a *positive learning effect* for construction within the set of 'similar' reactors (size and type). This observation pleads for standardization of future nuclear reactors.
- Constructing similar reactors (size & type) has allowed improvements in terms of safety.

Definitions, Conventions …

Inflation – Escalation

- Cost escalation in FR mainly due to the scaling-up strategy
- Scaling up and the FR drive to "*frenchify*" their reactors is associated with longer lead times and increased complexity, leading in turn to an increased cost/kW.
- Lévêque recommends the (not surprising) strategy:

the number of different technologies should be limited, standardization should be high on the wish list together with more off-site (i.e., within the factory) modular construction, so as to obtain learning effects that lead to lower construction costs and better performance in operation and safety performance.

Table of Contents

Definitions, Conventions …

Inflation – Escalation

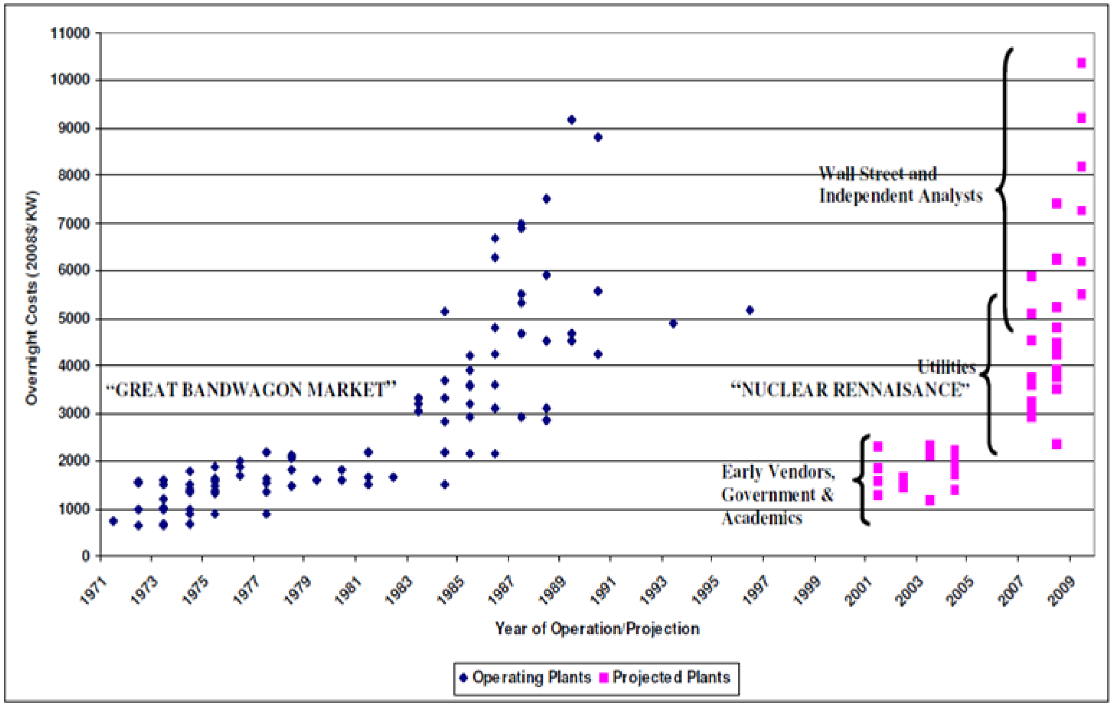
Learning Effects / Fleet Effect

Current construction costs Olkiluoto3 and Flamanvile

cost-estimate increases in USA (MIT/Uchicago)

not encouraging

Leads to figures like →



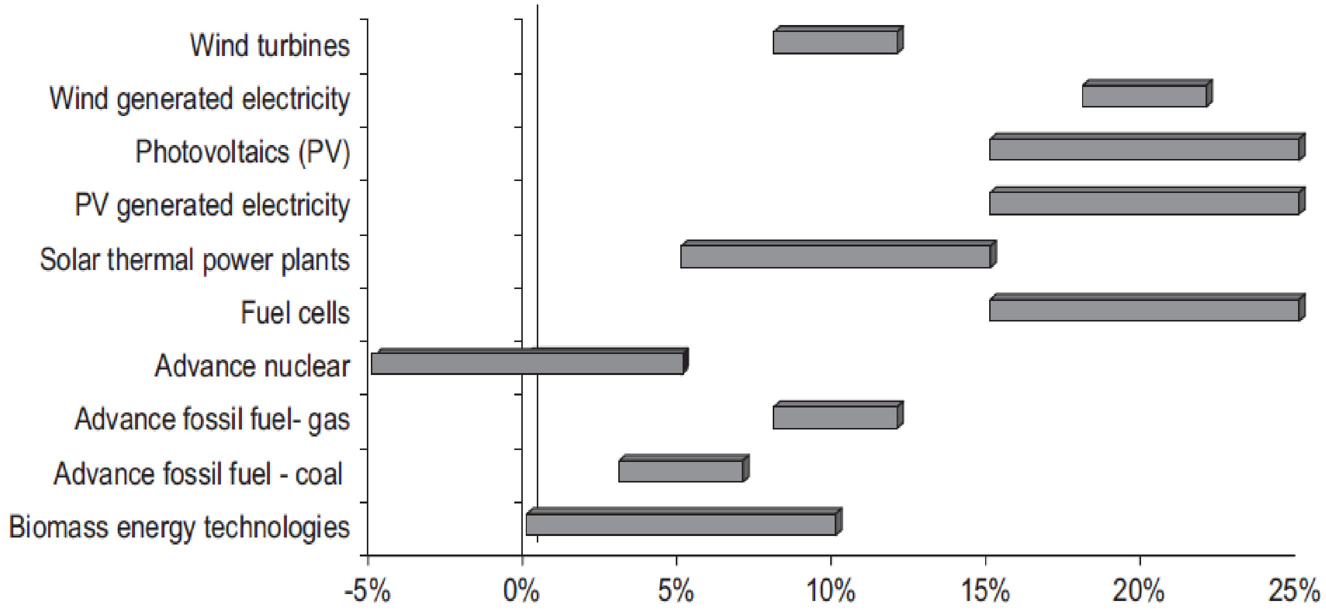
Sources: Koomey and Hultman, 2007, Data Appendix; University of Chicago 2004, p. S-2, p. S-8; University of Chicago estimate, MIT, 2003, p. 42; Tennessee Valley Authority, 2005, p. I-7; Klein, p. 14; Keystone Center, 2007, p.42; Kaplan, 2008 Appendix B for utility estimates, p. 39; Harding, 2007, p. 71; Lovins and Shiekh, 2008b, p. 2; Congressional Budget Office, 2008, p. 13; Lazard, 2008, Lazard, p. 2; Moody's, 2008, p. 15; Standard and Poor, 2008, p. 11; Severance, 2009, pp. 35-36; Schlissel and Biewald, 2008, p. 2; Energy Information Administration, 2009, p. 89; Harding, 2009. PPL, 2009; Deutch, et al., 2009, p. 6. See Bibliography for full citations.

Definitions, Conventions …

Inflation – Escalation

Learning Effects / Fleet Effect

L. Neij / Energy Policy 36 (2008) 2200–2211



Definitions, Conventions …

Inflation – Escalation

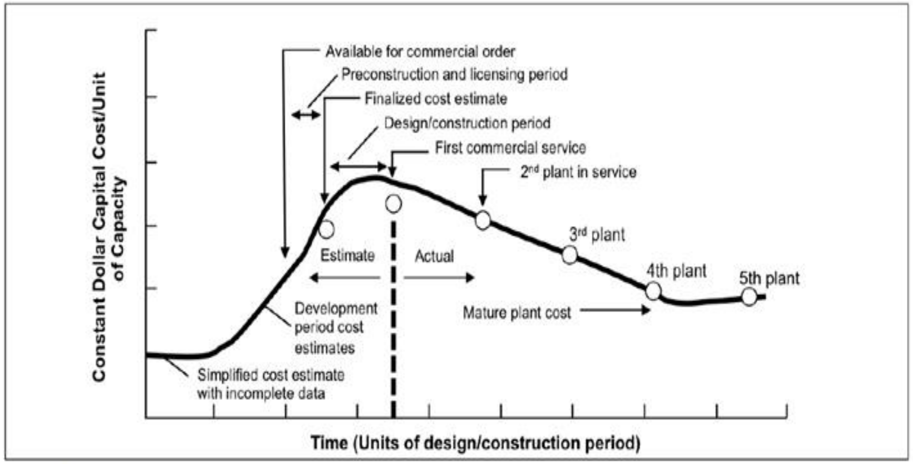
Learning Effects / Fleet Effect → Define two types of **FOAK** (First of a Kind):

- **$FOAK_1$**: the very first plant of a particular type that is built, regardless of where it is built (e.g., the EPR in Finland, AP1000 in China).
- **$FOAK_2$**: a first plant of a certain type in a particular country. E.g., EPR in Flamanville (FR)
- **NOAK**: "routine construction" as of the 5-th or 6-th reactor of the same type in the same country : denoted by **$NOAK_2$ (5+)** or **$NOAK_2$ (6+)**
- Also, to distinguish btwn **greenfield** or **brownfield**; one **single** unit is built or **twin** units are built, or part of a **fleet of, say 8** identical plants to be built in series.

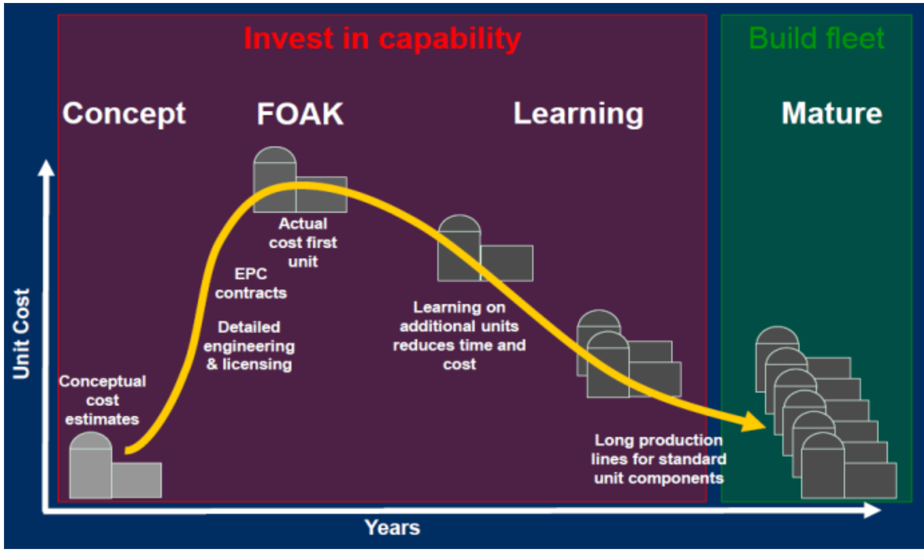
Definitions, Conventions …

Inflation – Escalation

Learning Effects / Fleet Effect



Source: *EPRI Program on Technology Innovation: Integrated Generation Technology Options*, June 2011.



Definitions, Conventions …

Inflation – Escalation

Learning Effects / Fleet Effect

- Engineering Consultant Mott MacDonald, involved in the analyses in the UK [MMD, 2011] considers that there is a current market mark-up (due to market congestion or distortions) of over 20%, which should be eliminated by 2020.

  For further cost reductions up to 30%-35% for NOAK-type of plants, it will *«require that the construction process in the future moves away from current substantial requirement for onsite labour, through better logistics control and/or increased reliance on offsite modular assembly.»*

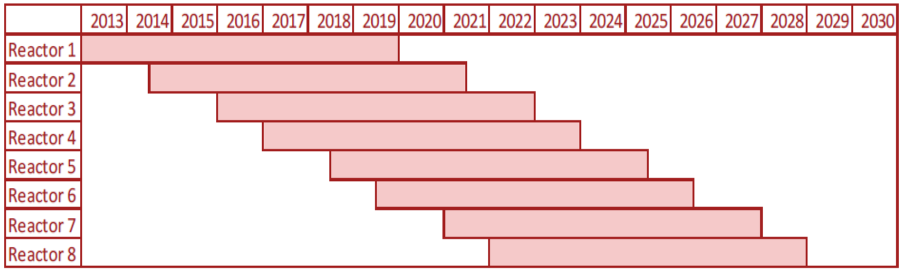
Definitions, Conventions …

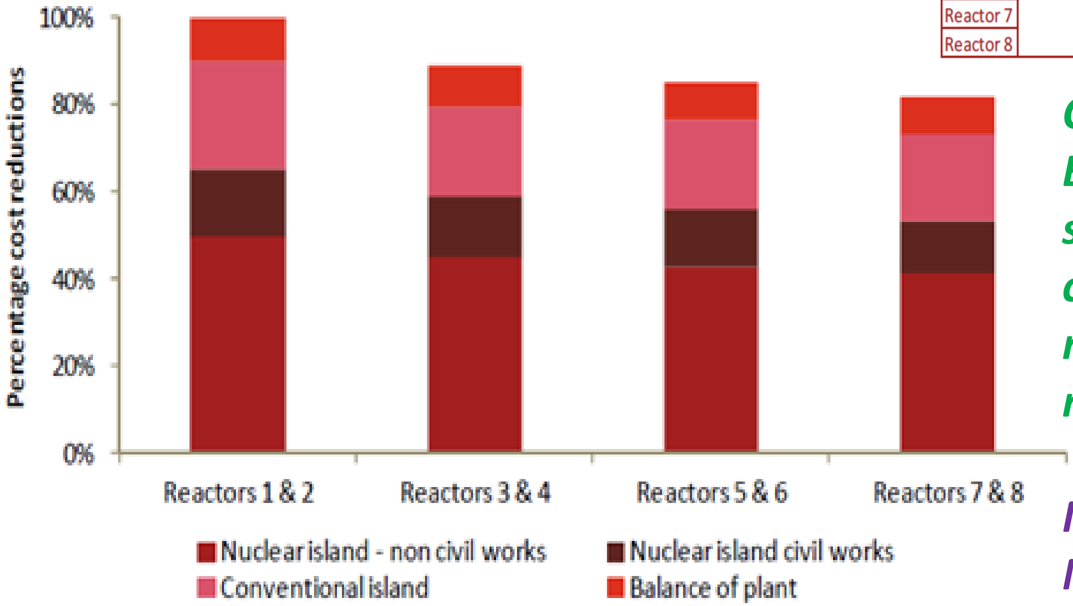
Inflation – Escalation

Learning Effects / Fleet Effect

Study PWC 2012 for UK

2nd pair would be 11% cheaper. 3rd & 4-th pair each time lead to a further cost saving of about 4%.
→ Reactors 7&8 about 18% cheaper





Compatible with Parsons Brinckerhoff's (2011) study for DECC: saving of 15% for the total capital costs of a nuc pwr station with multiple reactors, as construction moves from FOAK to NOAK in the UK.

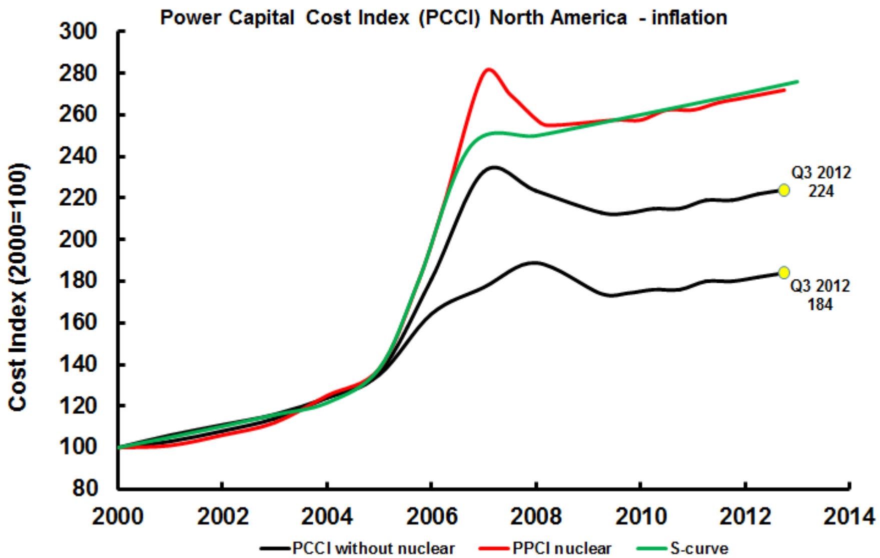
Mott MacDonald (2010) mentions NOAK/FOAK2 reduction by ~ 25%

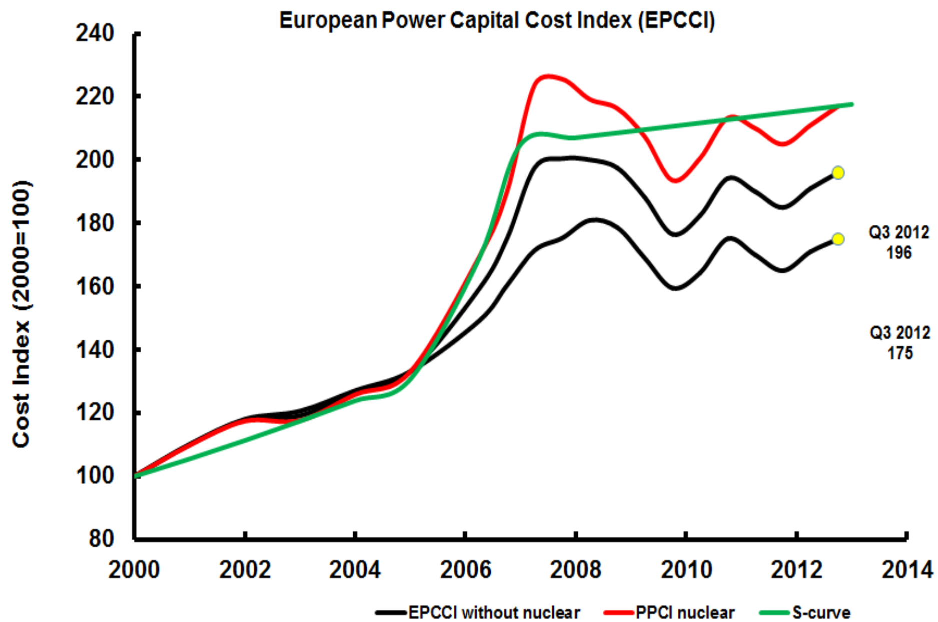
Table of Contents

Definitions, Conventions …

Inflation – Escalation

Pragmatic Approach on Cost Escalation – Own Analysis





Red curves are PCCIs for nuclear only – estimates
Green curves are simplifying fits / ignorig overshoot

Table 2.5: Approximate escalation factor for nuclear-only construction in the past (2000-2013)
In conclusion, we consider that:

Definitions, Conventions …

Inflation – Escalation

Pragmatic Approach on Cost Escalation – Own Analysis

North America	Annual percentage growth		EUR	Annual percentage growth
2000-2005	~ 5%/a		2000-2005	~ 5.5%/a
2005-2007	~ 26%/a		2005-2007	~ 25%/a
2007-2013	~ 2%/a		2007-2013	~ 1%/a

Future escalation? Perhaps normal inflation and 5%/a;
But we'll consider margin of uncertainties

Table of Contents

Definitions, Conventions …

Discount Rates / WACC definition

$$WACC = r_{debt}\left(\frac{D}{V}\right)(1 - t_c) + r_{equity}\left(\frac{E}{V}\right)$$

with

$$r_{debt} = \text{interest rate on debt}$$

$$r_{equity} = \text{expected rate of return rate for share holders}$$

$$V = \text{total Volume of capital to be covered}$$

$$D = \text{amount of Debt}$$

$$E = \text{amount of Equity}$$

$$t_c = \text{corporate tax rate}$$

$$V = D + E$$

Typically for private investors: D/V and E/V 50%/50%
or 40%/60% or vice versa

Definitions, Conventions …

Discount Rates / WACC definition

Derived discount rates:

- Gross nominal discount rate

$$\left(r_{eff}\right)^{nom} = r_{debt}\left(\frac{D}{V}\right) + r_{equity}\left(\frac{E}{V}\right)$$

MIT, 2003 and 2009
$(r_{eff})^{nom}$ = 11.3%; WACC = 10%
r_{debt}= 8% r_{equity}= 15%
50/50 debt/equity; corp tax 38%

- Real (gross) discount rate

$$\left(r_{eff}\right)^{real} = \frac{1+\left(r_{eff}\right)^{nom}}{1+i} - 1$$

with

i = inflation rate.

MIT, 2003 and 2009
i=3%/a → $(r_{eff})^{real}$ = 11.3%

MIT values are for <u>private</u> investors; for NPPs in liberalized markets discount rate penalty of ~3%-pt

For <u>public</u> investors, $(r_{eff})^{nom}$ ~ 3-4%/a (all debt; through –government – bonds)

Definitions, Conventions …

Discount Rates / WACC definition

Discount rates used in this study:

5%/a and 10%/a in real terms

Table of Contents

Table of Contents

Definitions, Conventions …

Uncertainties and Accuracy of Estimate

Level of Accuracy of the cost estimate:

Association for the Advancement of Cost Engineering International; Recommended Practice 18R-97

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

[b] If the range index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Definitions, Conventions …

Uncertainties and Accuracy of Estimate

Level of Accuracy of the cost estimate:

Our estimates:

$FOAK_2$; generic estimate btwn classes 3 and 5

→ accuracy btwn **-20% to +30%**

$NOAK_2$(5+) btwn classes 1 and 3

→ accuracy btwn **-10% to +15%**

Definitions, Conventions …

Uncertainties and Accuracy of Estimate

Contingency:

Based on AACE classes and estimates in the literature, for NPPS:

- **$FOAK_1$** contingency 30-50% (but not relevant to our report);
- **$FOAK_2$** contingency 15-30% (depending on the country; the low end would be if it concerns the 10-th plant ever of that type, the high end as long as no more than e.g., 5 units of that type have been built);
- **$NOAK_2$(10+)** 10-15% seems reasonable

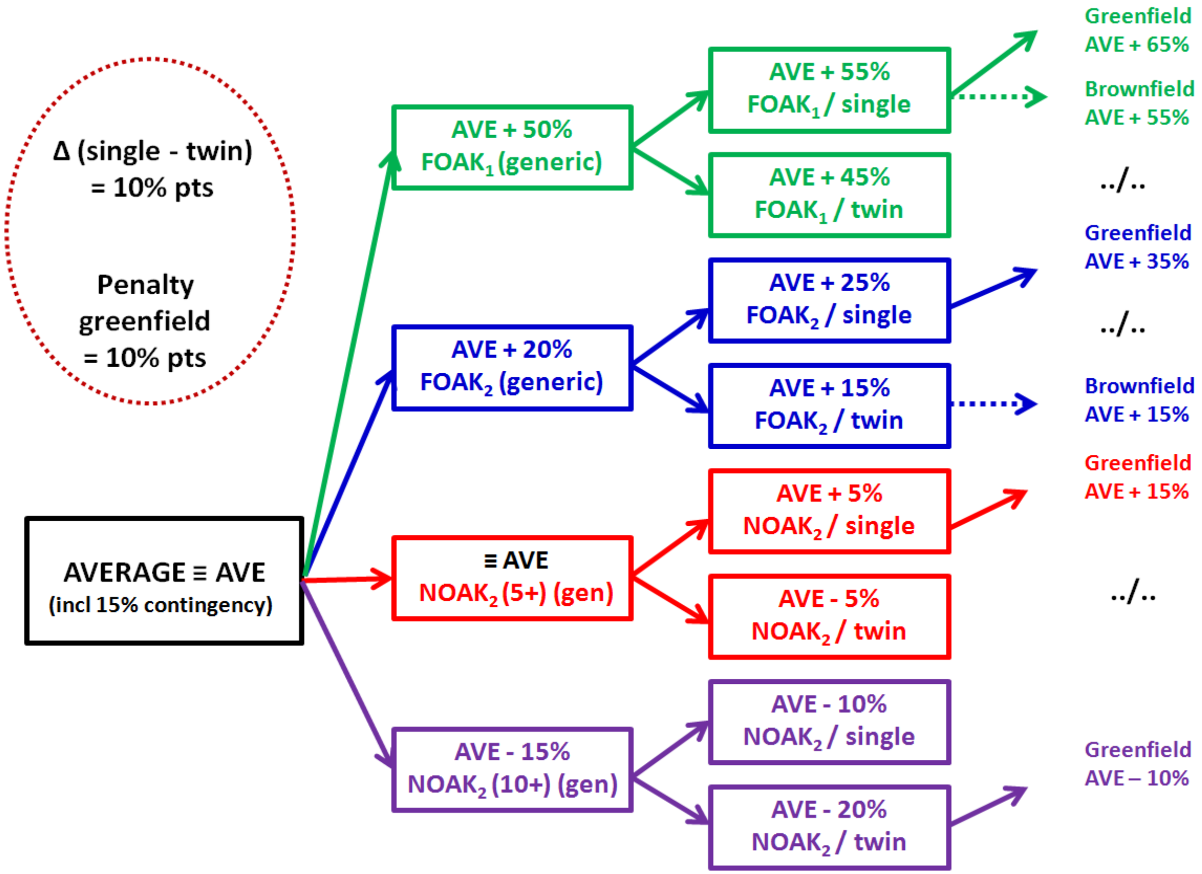
We take a *generic* contingency of 15%

for $NOAK_2$(5+) and set penalties for $FOAK_2$

Definitions, Conventions …

Uncertainties and Accuracy of Estimate

Proposed Overnight Capital Cost (OCC) levels:



Definitions, Conventions …

Uncertainties and Accuracy of Estimate

Proposed Overnight Capital Cost (OCC) levels:

- *Overall generic contingency (all kinds of reactor types) = 15%*
- *Generic average estimate applies to a $NOAK_2$(5+) reactor, single on a brownfield –expressed in constant EUR 2012*
  - *For $FOAK_2$ reactor: a generic penalty of +20%*
  - *For twin units, a bonus/advantage of 10%pts per unit*
  - *For greenfield construction: a penalty of 10%pts*
- *Overall accuracy on final result is*
  - *For $FOAK_2$: -20% to + 30%*
  - *For $NOAK_2$ (5+): -10% to + 15%.*

Table of Contents

Table of Contents

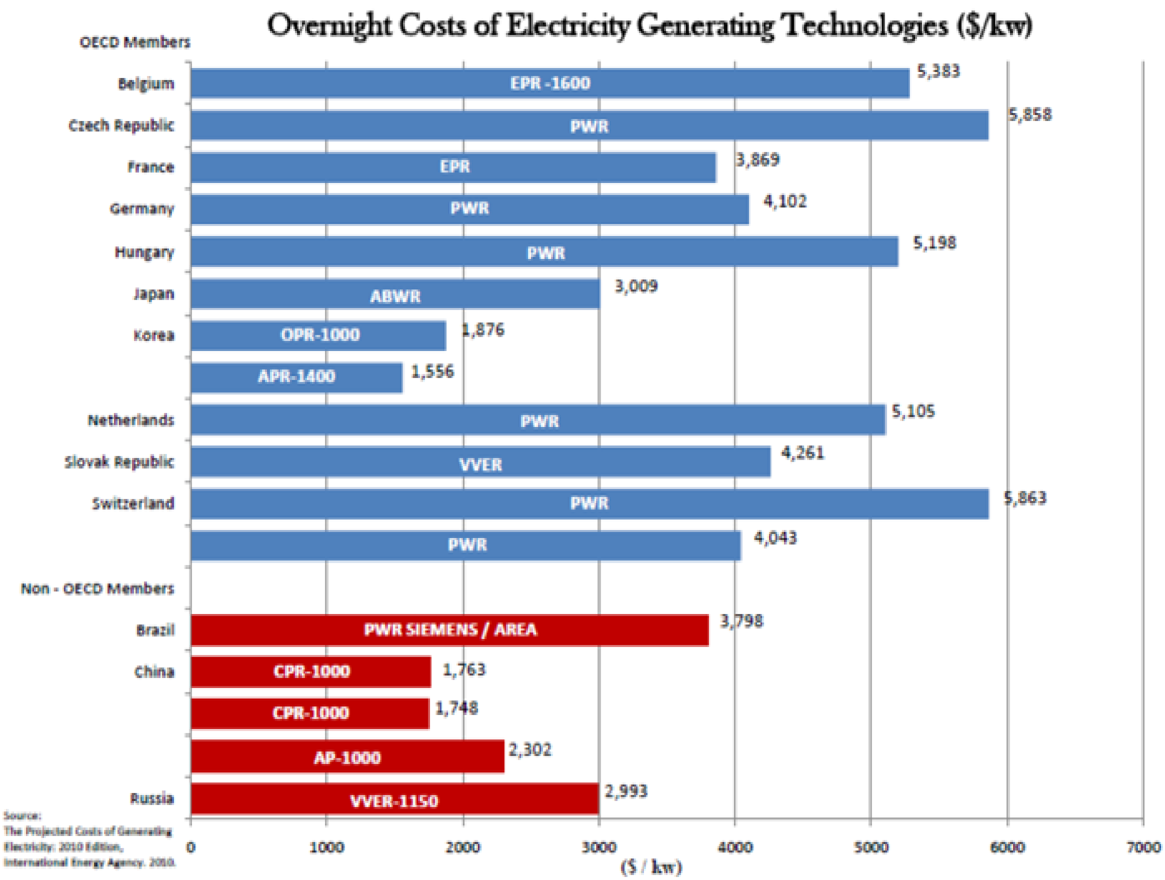
First attempt to converge on

Overnight Capital Construction Cost

Table of Contents

Investment Cost of New NPPs

Variation of estimates – Illustrations **– geographical**



NEA/IEA 2010

Investment Cost of New NPPs

Variation of estimates – Illustrations

– difference estimates vs real construction cost

Table 13.11: **Average Estimated and Realised Investment Costs of Nuclear Power Plants by Year of Construction Start, 1966-1977** ($2005 per kW)

Year of construction start	Number of plants	Initial estimate	Realised costs
1966-1967	11	530	1 109
1968-1969	26	643	1 062
1970-1971	12	719	1 407
1972-1973	7	1057	1 891
1974-1975	14	1095	2 346
1976-1977	5	1413	2 132

Note: Original data expressed in $1982.
Source: EIA/US DOE (1986).

Investment Cost of New NPPs

Variation of estimates – Illustrations

– variation in time of 'recent' estimates

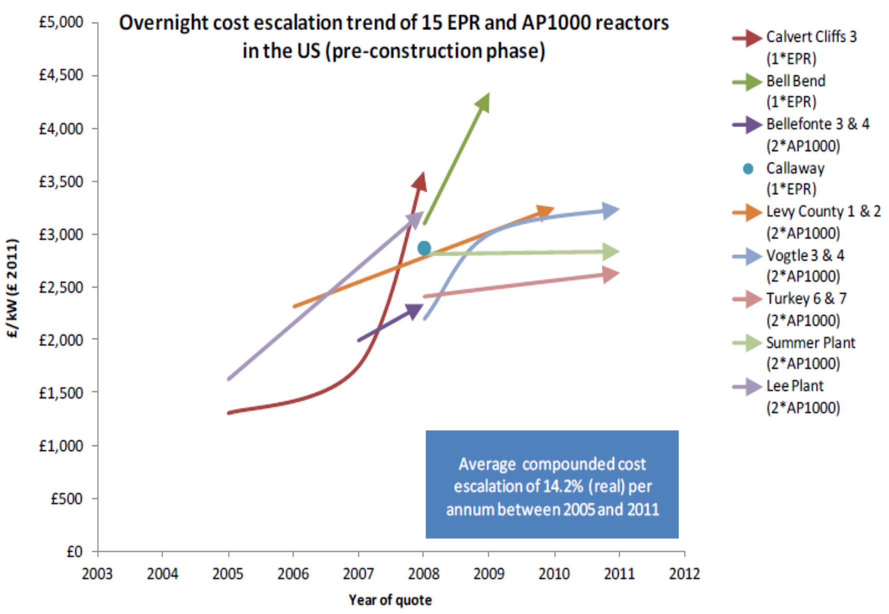


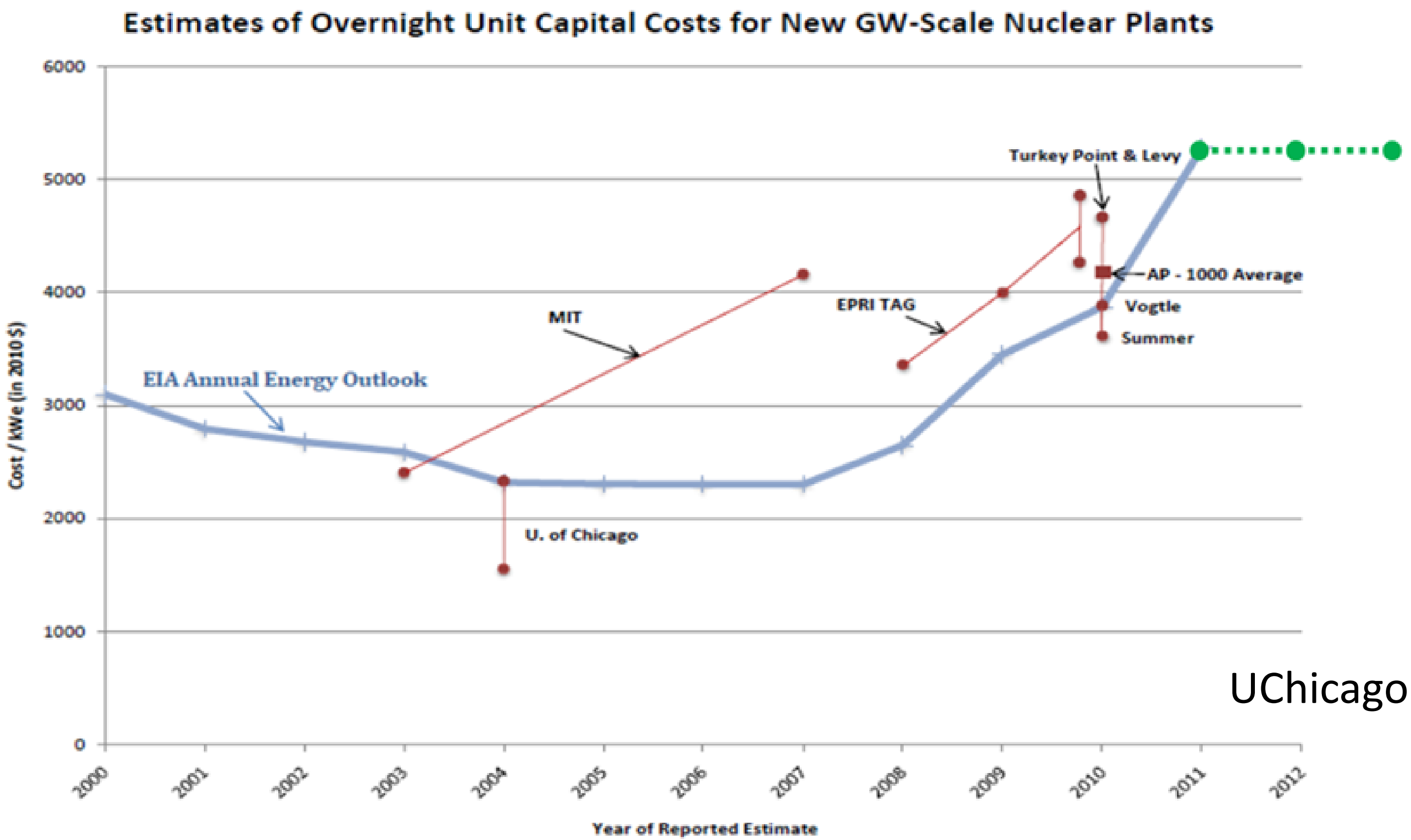
Figure 3: Overnight cost escalations in the pre-construction phase of US reactors between 2005 and 2011 (EPR and AP1000 reactor types only). All costs are expressed in 2011 values using the US CPI to index historic costs. For the Bell Bend and Callaway plants, where pure overnight cost estimates were not available, we have reduced quoted construction cost estimates by 23% (the average reduction that was experienced from other US plants in this analysis). Data sources are diverse and of varying credibility and content, so emphases should be placed on overall trends in the data, rather than on individual project-level estimates. Source: Authors own analysis from a range of sources outlined in Appendix 1.

ICEPT 2012
Imperial College

Investment Cost of New NPPs

Variation of estimates – Illustrations

– variation in time of 'recent' estimates



UChicago 2011

Table of Contents

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

- Whole variety of estimates, optimistic, pessimistic
- Often controversial views:
  - [Cooper, 2009] criticizes the results of the [MIT, 2009] update as being too optimistic
  - [Rothwell, 2010] criticizes that same [MIT, 2009] update result as being too pessimistic

- All in all, we have retained 137 data points for the **Overnight Construction Cost** from 28 sources.

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

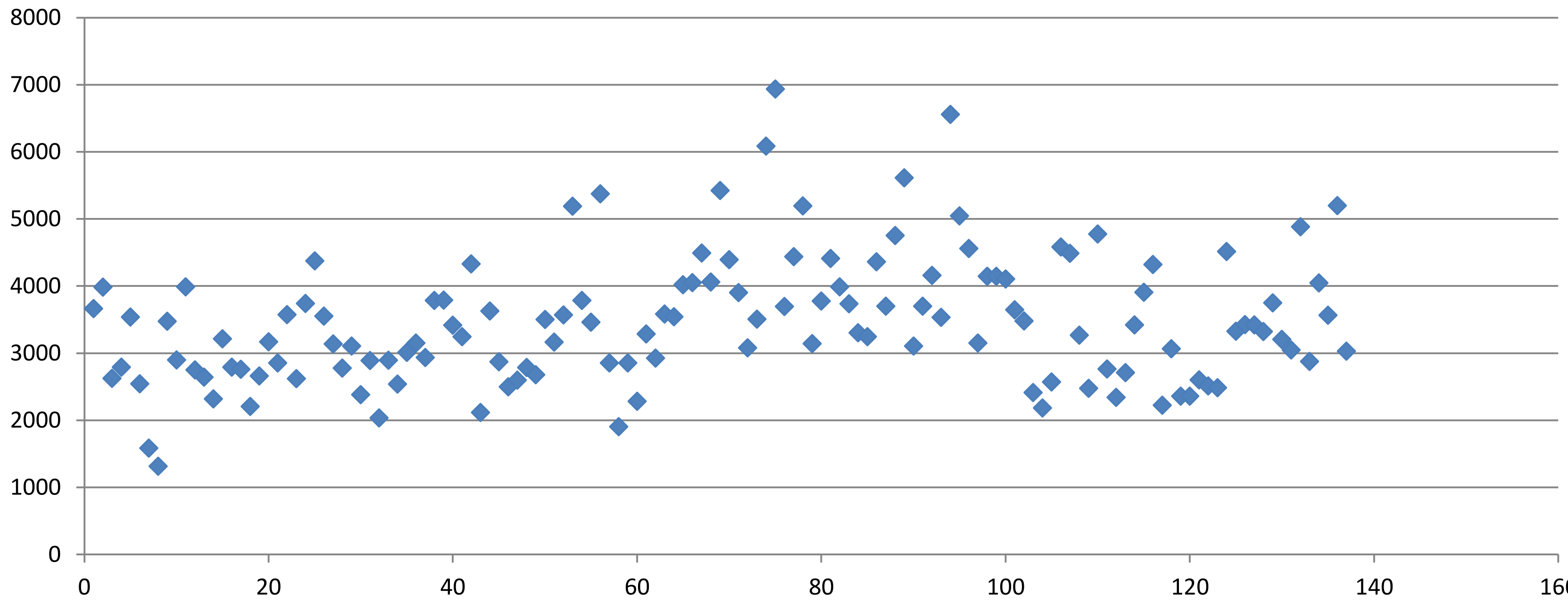
NEA/IAE 2010	(17 data)
Du & Parsons 2009	(18 data)
U Chicago Update 2011	(7 data)
CEU COMM 2008	(3 data)
Rothwell June 2010	(5 data)
EPRI Update June 2011	(2 data)
LUT 2012	(2 data)
Lazard 2008-11-12	(2 data)
IEA Stuttgart 2010	(1 data)
ECN 2010	(3 data)
ICEPT 2012	(15 data)
Parsons Brinckerhoff 2011	(6 data)
MMD 1010 and 2011	(5 + 6 data)

Black & Veatch 2012	(3 data)
USC 2010 & 2011	(1 + 12 data)
Calif En Comm (CEC) 2010	(1 data)
BERR 2012	(2 data)
CBO 2008	(1 data)
Harding 2008	(4 data)
EIA AEO 2013	(1 data)
Keystone 2007	(1 data)
Severance 2009	(1 data)
Cooper 2009 (-10-11)	(14 data)
CRS (Kaplan) 2008	(1 data)
Lévêque 2013	(2 data)
VGB 2012	(1 data)

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

Scatter plot of results ($EUR_{2012}/kW_{installed}$)

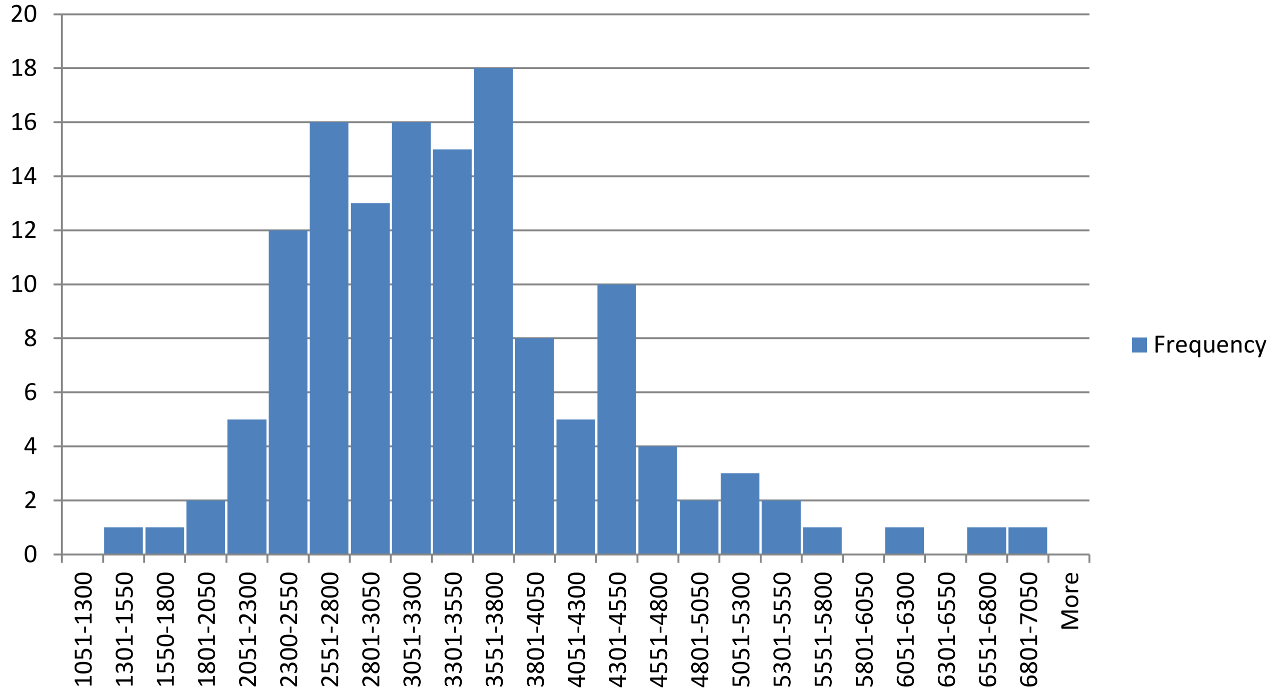


Scatter plot for the 137 data points for the overnight construction cost (OCC) from a disparate set of references (mostly PWRs, but also a few BWRs, and so-called "generic" plants)

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

Histogram for the results (*EUR*$_{2012}$/*kW*$_{installed}$)

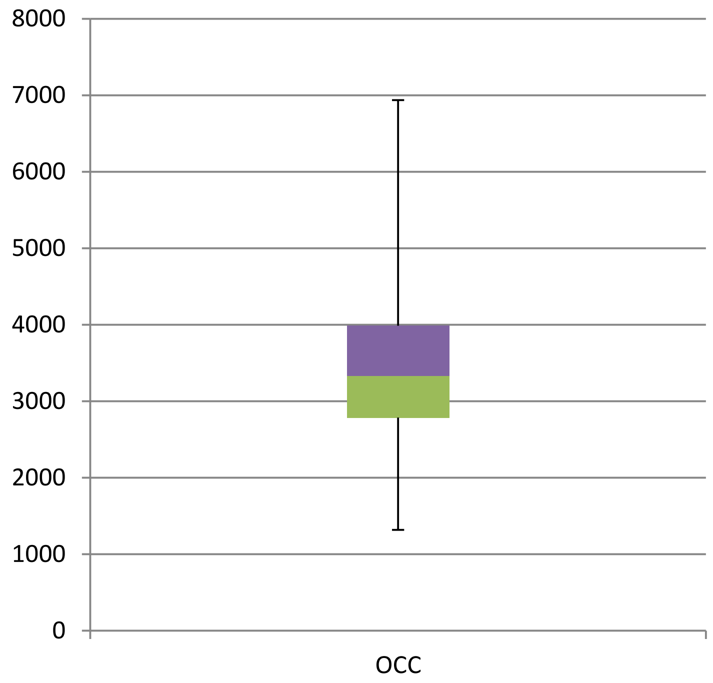


Histogram for the 137 data points for the overnight construction cost (OCC) from a disparate set of references (mostly PWRs, but also a few BWRs, and so-called "generic" plants). The intervals of the bins are 250 EUR$_{2012}$ wide.

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

Box plot for the results (*EUR₂₀₁₂/kW*)



The following parameters apply:

Minimum = 1316 €'$_{12}$/*kW*

Median = 3320 €'$_{12}$/kW

Maximum = 6934 €'$_{12}$/*kW*

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

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

Median = 3320 €'$_{12}$/kW **Mean = 3447.5 €'$_{12}$/kW**

Define "***AVERAGE***" as (MEAN + MEDIAN)/2 = 3383.7

→ roughly ***3400 €'$_{12}$/kW***

= about **3400 EUR$_{2012}$/kW** for **NOAK$_2$ (5+)** with uncertainty - 10% to + 15% on a brownfield, as generic estimate (single/twin)

= about **3230 EUR$_{2012}$/kW** for **NOAK$_2$ (5+)** with uncertainty -10% to + 15% on a brownfield, for a **twin** unit

= about **3570 EUR$_{2012}$/kW** for **NOAK$_2$ (5+)** with uncertainty -10% to + 15% on a brownfield, for a **single** unit

Investment Cost of New NPPs

Pre-Consultation Capital Cost Estimate

$FOAK_2$:

= about **$3910\ EUR_{2012}/kW$** for **$FOAK_2$** with uncertainty -20% to + 30% on a brownfield, for a twin unit

= about **$4250\ EUR_{2012}/kW$** for **$FOAK_2$** with uncertainty -20% to + 30% on a brownfield, for a single unit

Table of Contents

Intermediate Report – for consultation

Synthesis on the economics of nuclear energy

Study for the European Commission, DG Energy

Service Contract N° ENER/2012/NUCL/SI2.643067

Draft Intermediate Report

May 20, 2013

William D. D'haeseleer

Version 1.0_1

Submitted: May 20, 2013

ENEF SC reporting: June 21, 2013

Review / Consultation after Prelim Report

1. Academic Reviewers
2. Industrial Players

Review / Consultation after Prelim Report

1. Academic Reviewers
2. Industrial Players

Review / Consultation after Prelim Report

1. Academic Reviewers

   - William Nuttall – Open University, UK
   - John Parsons – MIT, USA
   - Jan-Horst Keppler – Univ Dauphine Paris, FR
   - François Lévèque –Mines Paris Tech, FR

Review / Consultation after Prelim Report

1. Academic Reviewers
2. Industrial Players

Review / Consultation after Prelim Report

2. Industrial Players
   - Areva
   - Westinghouse
   - Rosatom
   - EdF
   - GdF-Suez
   - TVO
   - CEZ
   - WNA
   - VGB / Eurelectric

Review / Consultation after Prelim Report

Generally positive feedback, with praise for scope, definitions, delineations of cost factors;

No fundamental disagreements or issues;

and

(Minor) requests for for further clarification on goal of "average estimate" (statistics), definition external costs, escalation a bit overdone,...

Review / Consultation after Prelim Report

Nobody of Industry ‘disagreed’ with value of estimate, generally in right ballpark, but requests to stress again differences (reactor types, geographical differences, regulatory influence,...)

Informal reactions industry mixed: some are unhappy with too high figures, others unhappy with too low figures...

Review / Consultation after Prelim Report

- **Recall our OCC generic estimate: 3,400 €$_{2012}$/kW**
  - **Applicable for NOAK$_2$(5+)**
  - **On a brownfield**
  - **No distinction Single/Twin**
  - **Uncertainty range btwn – 10% to + 15%**

Review / Consultation after Prelim Report

- 'Utility' / Electricity Generator (anonymous):
  - *«the orders of magnitude are coherent with what we see inprojects we are developing» ... [But]... «we make a clear distinction between a European and a world average»*
  - **3,750 €/kW** Europe
  - **2,350 €/kW** world average

Review / Consultation after Prelim Report

- Westinghouse:
  - **4,200 €/kW** Europe (range btwn 3,600 to 4,900 €/kW) *twin* units
  - 5,040 €/kW Europe for *single* units (factor 1.2)
- Rosatom:
  - «OCC realized in Russia is in range btwn **2,575** and **3,526** €$_{2012}$/kW»
- Areva:
  - «The resulting "Average", used as a generic case, is not far from sources like the IEA WEO which is broadly recognised – OCC Europe **4,000 $/kW**»
  - «Results coming from methodology of this study are also in line with today's ongoing nuclear projects. E.g., the cost of the EPR in Flamanville as publically quoted by EdF is ... **4,900 to 5,150 €/kW**, close to your result of **5,270 €/kW** for FOAK$_1$ single unit on Brownfield»
  - Actually EPR Flam is a FOAK$_2$ single unit on Brownfield → 4,250 €/kW uncertainty -20% to +30% → Range spans 3,400...5,525 €/kW

Table of Contents

Post-Consultation Wrap Up

- **Recall our OCC generic estimate: 3,400 €$_{2012}$/kW**
  - For **NOAK$_2$ (5+)** on a **brownfield**
  - But with uncertainty range btwn **– 10% to + 15%**
  - Hence, estimate: 3,060 ...**3,400**...3,910 €$_{2012}$/kW

- Recall **FOAK$_2$ single** unit on **brownfield**: **4,250 €/kW** uncertainty -20% to +30%

  → Range spans 3,400...**4,250**...5,525 €/kW

Post-Consultation Wrap Up

Attempts to more 'Europeanize' average estimate:

1) Take out the Asian (Korea & Japan) numbers from data base (especially [NEA/IEA, 2010] and [MIT, 2010]) to rely only on "Western", i.e., European and USA numbers:

→ leads to Median=3,445 & Mean=3,541

→ Average = 3,493 → **About 3500 $€_{2012}$/kW generic**

2) Take out the Asian (Korea & Japan) & USA numbers from data base [NEA/IEA, 2010] to rely only on European numbers:

→ leads to Median=3,344 & Mean=3,292

→ Average = 3,318 → **About 3300 $€_{2012}$/kW generic**

→ No unidirectional guidance to upgrade numbers…

Post-Consultation Wrap Up

Recently "discovered" new numbers:

Hirschberg et al. "Review of current and future nuclear technologies"
PSI Scientific Highlights 2011

- Mostly on External costs & accidents
- New NPP for Switzerland,

OCC : 2,900...**3,540**...4,200 €/kW

[PB, 2012] & [PB 2013] for UK (medium estimates):

'12 → **4,217** $€_{2012}$/kW for NOAK (3 units), and **4,960** $€_{2012}$/kW for $FOAK_2$ (3 units)

'13→ **4,762** $€_{2012}$/kW for NOAK (3 units), and **5,452** $€_{2012}$/kW for $FOAK_2$ (3 units)

For consistency of methodology, these numbers were not incorporated in data base!

Post-Consultation Wrap Up

Conclusion on OCC

However, to accommodate the clear signal from the industrial actors, and endorsed by the ENEF Steering Committee, it makes sense for Europe, to ***emphasize the high uncertainty bracket of estimate*** and to attach less importance to the lower end of the uncertainty range.

This would mean that our recommended estimate for the OCC in the end is as follows:[80]

For $NOAK_2$ (5+) on a brownfield:	3,060…**3,400…3,910** €$_{2012}$/kW
For $FOAK_2$ twin unit on brownfield:	3,128…**3,910…5,083** €$_{2012}$/kW
For $FOAK_2$ single unit on brownfield:	3,400…**4,250…5,525** €$_{2012}$/kW

Table of Contents

Investment for LTO / Refurbishments

- Range of Overnight Refurbishment Cost **~ 500 – 1,100 $/kW**

or with 1 $\$_{2010}$ = 0.754 $€_{2010}$ → range ~ 377 – 830 €/kW,

or thus **~ 400 – 850 $€_{2012}$/kW for additional lifetime of up to ~ 20 years**

Note: $€_{2010}$ = 1.02 $€_{2012}$ (adapted nuclear S curve Europe)

Table of Contents

Recall: Results for LCOE - NEA/IEA (2010)

Table 3.7a: Nuclear power plants: Levelised costs of electricity in US dollars per MWh

Country	Technology	Net capacity	Overnight costs[1]	Investment costs[2]		Decommissioning costs		Fuel Cycle costs	O&M costs[3]	LCOE	
				5%	10%	5%	10%			5%	10%
		MWe	USD/kWe	USD/kWe		USD/MWh		USD/MWh	USD/MWh	USD/MWh	
Belgium	EPR-1600	1 600	5 383	6 185	7 117	0.23	0.02	9.33	7.20	**61.06**	**109.14**
Czech Rep.	PWR	1 150	5 858	6 392	6 971	0.22	0.02	9.33	14.74	**69.74**	**115.06**
France*	EPR	1 630	3 860	4 483	5 219	0.05	0.005	9.33	16.00	**56.42**	**92.38**
Germany	PWR	1 600	4 102	4 599	5 022	0.00	0.00	9.33	8.80	**49.97**	**82.64**
Hungary	PWR	1 120	5 198	5 632	6 113	1.77	2.18	8.77	29.79/29.84	**81.65**	**121.62**
Japan	ABWR	1 330	3 009	3 430	3 940	0.13	0.01	9.33	16.50	**49.71**	**76.46**
Korea	OPR-1000	954	1 876	2 098	2 340	0.09	0.01	7.90	10.42	**32.93**	**48.38**
	APR-1400	1 343	1 556	1 751	1 964	0.07	0.01	7.90	8.95	**29.05**	**42.09**
Netherlands	PWR	1 650	5 105	5 709	6 383	0.20	0.02	9.33	13.71	**62.76**	**105.06**
Slovak Rep.	VVER 440/ V213	954	4 261	4 874	5 580	0.16	0.02	9.33	19.35/16.89	**62.59**	**97.92**
Switzerland	PWR	1 600	5 863	6 988	8 334	0.29	0.03	9.33	19.84	**78.24**	**136.50**
	PWR	1 530	4 043	4 758	5 612	0.16	0.01	9.33	15.40	**57.83**	**96.84**
United States	Advanced Gen III+	1 350	3 382	3 814	4 296	0.13	0.01	9.33	12.87	**48.73**	**77.39**
NON-OECD MEMBERS											
Brazil	PWR	1 405	3 798	4 703	5 813	0.84	0.84	11.64	15.54	**65.29**	**105.29**
China	CPR-1000	1 000	1 763	1 946	2 145	0.08	0.01	9.33	7.10	**29.99**	**44.00**
	CPR-1000	1 000	1 748	1 931	2 128	0.08	0.01	9.33	7.04	**29.82**	**43.72**
	AP-1000	1 250	2 302	2 542	2 802	0.10	0.01	9.33	9.28	**36.31**	**54.61**
Russia	VVER-1150	1 070	2 933	3 238	3 574	0.00	0.00	4.00	16.74/16.94	**43.49**	**68.15**
INDUSTRY CONTRIBUTION											
EPRI	APWR, ABWR	1 400	2 970	3 319	3 714	0.12	0.01	9.33	15.80	**48.23**	**72.87**
Eurelectric	EPR-1600	1 600	4 724	5 575	6 592	0.19	0.02	9.33	11.80	**59.93**	**105.84**

*The cost estimate refers to the EPR in Flamanville (EDF data) and is site-specific.

Ref: NEA/IEA (2010) Table 3.7a

Fuel Cycle Costs and O&M Costs

- **Fuel cycle** cost contains full cycle:
  front end / upstream & back end / downstream
- NEA/IEA (2010) COE Report (p 42) mostly assumes:
  - Upstream fuel (assembly) cost= 7 $\$_{2008}/MWh_e$
  - Downstream (up to final disposal) = 2.33 $\$_{2008}/MWh_e$
- MIT & Du& Parsons (2009) take
  - Upstream cost = 6.97 $\$_{2007}/MWh_e$
  - Downstream cost (disposal SNF) = 1 $\$_{2007}/MWh_e$

Fuel Cycle Costs and O&M Costs

Comprehensive new study on back end of fuel cycle (with elements of front end costs):

NEA (draft summer 2013), **"*The economics of the back end of the nuclear fuel cycle*"**, Paris, 2013

- Makes interesting generic scenarios,
- Makes comparisons with other studies

  (e.g., MIT, The Future of the Nuclear Fuel Cycle", 2011)
- Gives full overview of the issues, regulatory aspects, national differences etc.

Fuel Cycle Costs and O&M Costs

- Three scenarios considered
  1. Direct disposal of spent nuclear fuel (SNF)
  2. Partial recycling in LWR

     Twice through (REPUOX and MOX) and disposal of the spent MOX and spent REPUOX
  3. Multiple Pu recycling with LWRs and FRs

     MOX and REPUOX recycling once in LWRs and multiple plutonium recycling in fast reactors

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

- **Overall Results**

Four systems: 25, 75, 400, 800 TWh/a

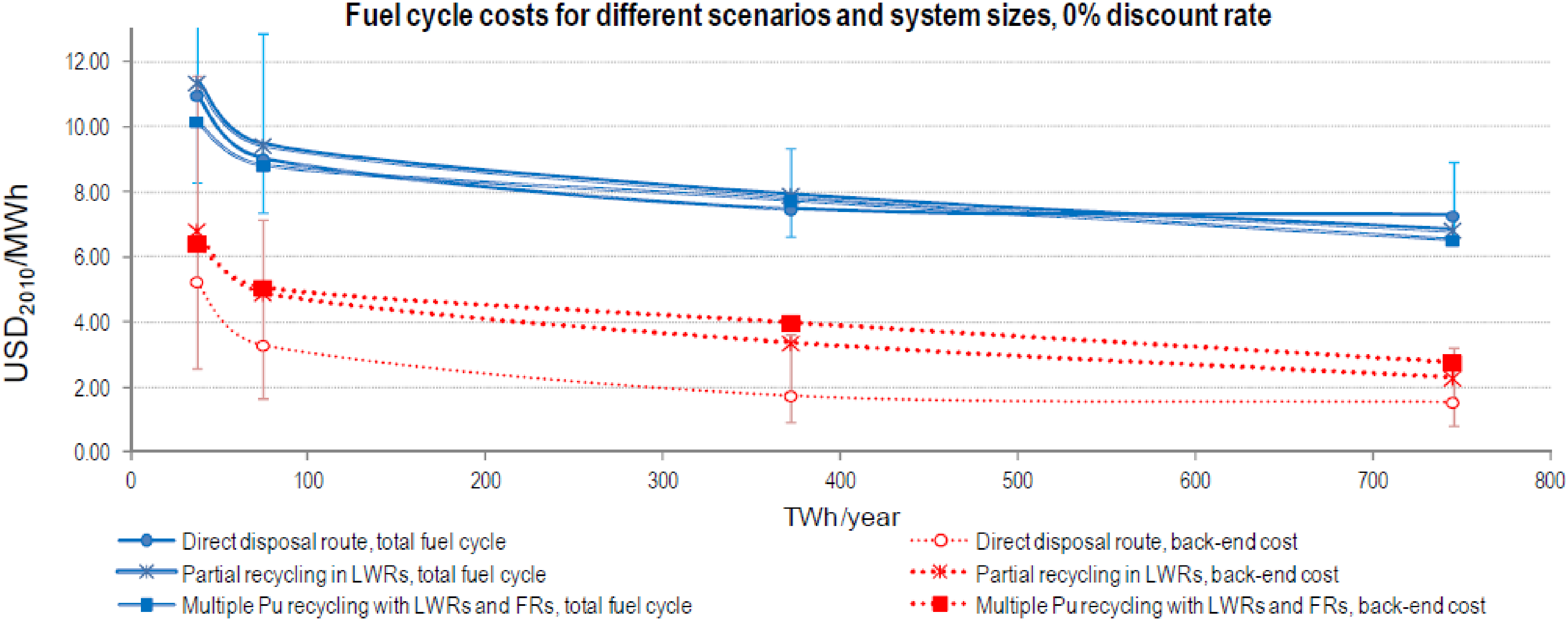
Note: Belgium ~50
Sweden ~60
UK ~ 70
FR ~ 400
USA ~ 800

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

- **Overall Results**

Four systems: 25, 75, 400, 800 TWh/a



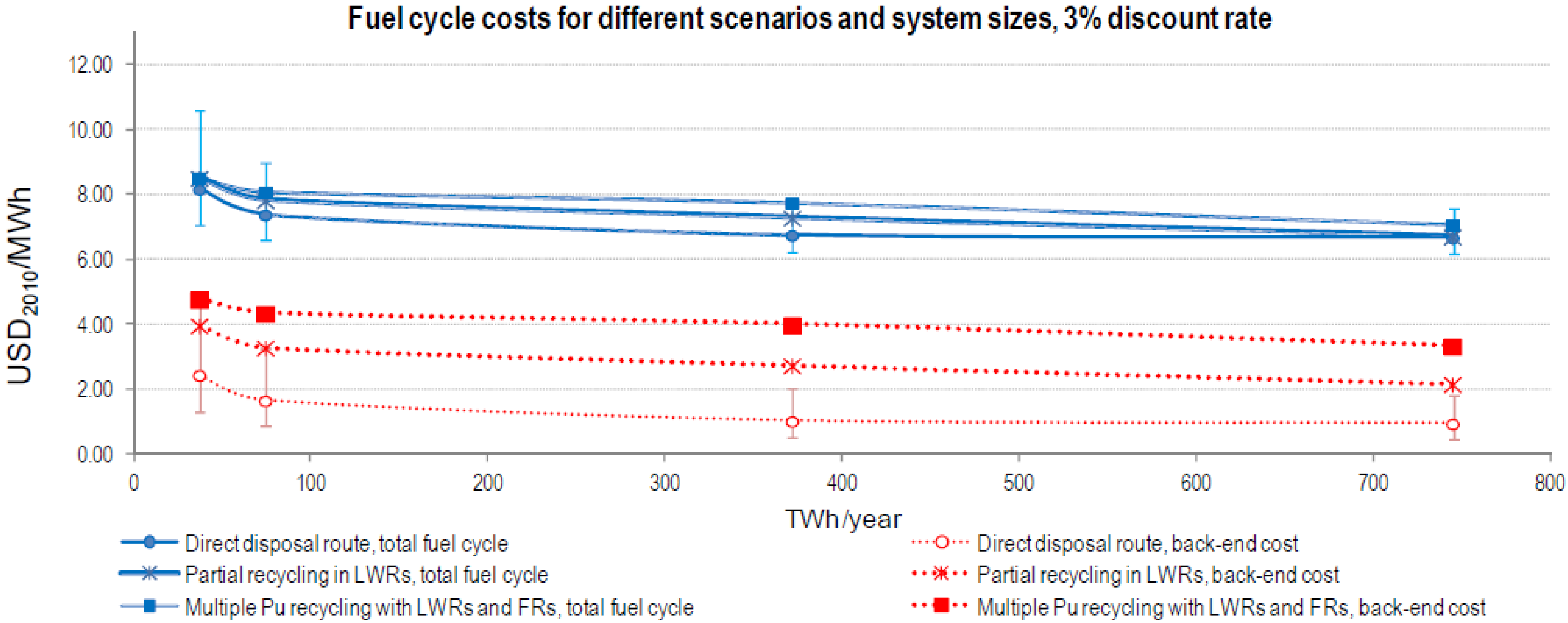
Note: Belgium ~50, Sweden ~60, UK ~ 70, FR ~ 400; USA ~ 800

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

Four systems: 25, 75, 400, 800 TWh/a

- **Overall Results**



Note: The central values were calculated within the REFERENCE cost scenario, and the error bars correspond to LOW and HIGH cost scenarios.

Note: Belgium ~50, Sweden ~60, UK ~ 70, FR ~ 400; USA ~ 800

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

- **Overall Results**

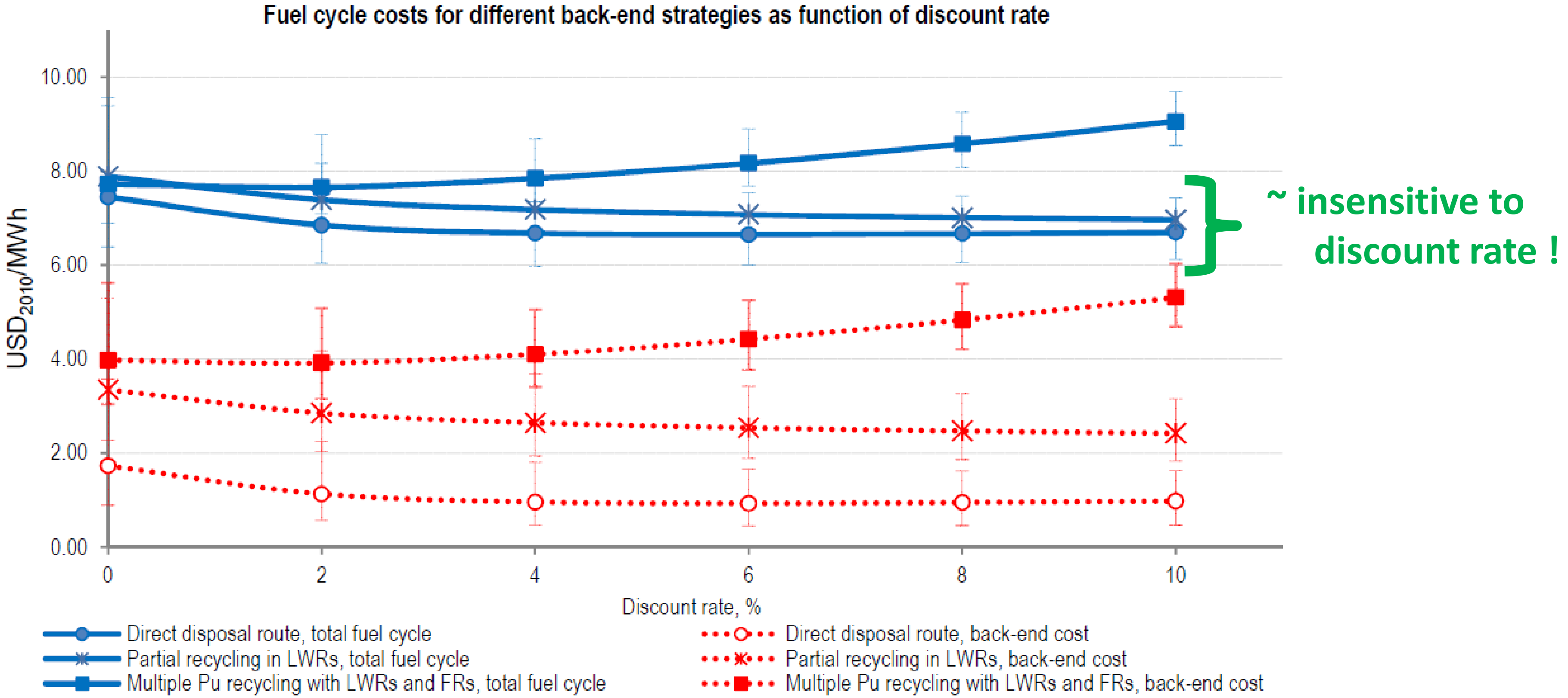
Bottomline conclusion:

- Cost once through ~ same as reprocessing!
- Extra cost reprocessing gained back in primary fuel
- Overall cost ~ **7-9 $\$_{2010}$/MWh**

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

Figure 3.28 Fuel cycle costs for different back-end strategies as function of discount rate, for a fleet generating 400 TWh/year



Note: The central values were calculated within the REFERENCE cost scenario, and the error bars correspond to LOW and HIGH cost scenarios.

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

Comparison with other studies

Table 3.10 Summary of modelling results

	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	*Results from Section 3.2, REFERENCE case, 3% discount rate*		
							System size		
							25 TWh/yr	400 TWh/yr	800 TWh/yr
Results:				Total FC/Back-end Costs					
Once-through, USD2010/MWh	6.7/**2.7**	8.2/**1.3**	9.4/**1.3**	5.6/**1.7**	7.5/**1.1**	6.5/**2.1**	8.9/**3.2**	6.7/**1.0**	6.8/**0.9**
Twice-through, USD2010/MWh	NA	9.7/**2.8**	10.4/**2.6**	6.4/**NA**	12.4/**6.7**	8.1/**3.8**	9.2/**4.6**	7.3/**2.7**	6.6/**2.1**
Adv. Recycling, USD2010/MWh	8.4/**6.0**	(10.3-11.3)/**(3.3-4.3)**	NA	7.0/**NA**	NA	9.2/**4.8**	8.9/**5.2**	7.7/**4.0**	7.0/**3.3**
FC cost premium for closed fuel cycle	26%	18-37%	14%	14%-25%	66%	25-42%	20%		

Units: **$$_{2010}$/MWh$_e$**

x/y total FC / back end

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

Generic fuel cycle cost

Results from Section 3.2, REFERENCE case, 3% discount rate		
System size		
25 TWh/yr	400 TWh/yr	800 TWh/yr
8.9/**3.2**	6.7/**1.0**	6.8/**0.9**
9.2/**4.6**	7.3/**2.7**	6.6/**2.1**
8.9/**5.2**	7.7/**4.0**	7.0/**3.3**

Units: **$\$_{2010}$/MWh$_e$**

x/y total FC / back end

Take as generic figure:
Total fuel cycle cost ~ **8 / 2 $\$_{2010}$ per MWh$_e$**

Or,
with 1 $\$_{2010}$ = 0.754 €$_{2010}$
and
€$_{2010}$ = 1.02 €$_{2012}$ (adapted nuclear S curve Europe)

Total fuel cycle cost ~ **6.15 / 1.55 €$_{2012}$ per MWh$_e$**

Generic order of magnitude fuel cycle cost
~ 6 / 1.5 €$_{2012}$ per MWh$_e$

Ref: **NEA**, ***"The economics of the back end of the nuclear fuel cycle"***, Paris, 2013

Fuel Cycle Costs and O&M Costs

- We started from 7 – 9 $\$_{2010}$, with central value 8 $\$_{2010}$
- Converted to $€_{2012}$, central value was 6 $€_{2012}$ / MWh_e

- **Hence estimate $LCOE_{fuel}$**

  ~ 6 $€_{2012}$ / MWh_e (± 0.75 $€_{2012}$ / MWh_e)

Recall: Results for LCOE - NEA/IEA (2010)

Table 3.7a: Nuclear power plants: Levelised costs of electricity in US dollars per MWh

Country	Technology	Net capacity	Overnight costs[1]	Investment costs[2]		Decommissioning costs		Fuel Cycle costs	O&M costs[3]	LCOE	
				5%	10%	5%	10%			5%	10%
		MWe	USD/kWe	USD/kWe		USD/MWh		USD/MWh	USD/MWh	USD/MWh	
Belgium	EPR-1600	1 600	5 383	6 185	7 117	0.23	0.02	9.33	7.20	**61.06**	**109.14**
Czech Rep.	PWR	1 150	5 858	6 392	6 971	0.22	0.02	9.33	14.74	**69.74**	**115.06**
France*	EPR	1 630	3 860	4 483	5 219	0.05	0.005	9.33	16.00	**56.42**	**92.38**
Germany	PWR	1 600	4 102	4 599	5 022	0.00	0.00	9.33	8.80	**49.97**	**82.64**
Hungary	PWR	1 120	5 198	5 632	6 113	1.77	2.18	8.77	29.79/29.84	**81.65**	**121.62**
Japan	ABWR	1 330	3 009	3 430	3 940	0.13	0.01	9.33	16.50	**49.71**	**76.46**
Korea	OPR-1000	954	1 876	2 098	2 340	0.09	0.01	7.90	10.42	**32.93**	**48.38**
	APR-1400	1 343	1 556	1 751	1 964	0.07	0.01	7.90	8.95	**29.05**	**42.09**
Netherlands	PWR	1 650	5 105	5 709	6 383	0.20	0.02	9.33	13.71	**62.76**	**105.06**
Slovak Rep.	VVER 440/ V213	954	4 261	4 874	5 580	0.16	0.02	9.33	19.35/16.89	**62.59**	**97.92**
Switzerland	PWR	1 600	5 863	6 988	8 334	0.29	0.03	9.33	19.84	**78.24**	**136.50**
	PWR	1 530	4 043	4 758	5 612	0.16	0.01	9.33	15.40	**57.83**	**96.84**
United States	Advanced Gen III+	1 350	3 382	3 814	4 296	0.13	0.01	9.33	12.87	**48.73**	**77.39**
NON-OECD MEMBERS											
Brazil	PWR	1 405	3 798	4 703	5 813	0.84	0.84	11.64	15.54	**65.29**	**105.29**
China	CPR-1000	1 000	1 763	1 946	2 145	0.08	0.01	9.33	7.10	**29.99**	**44.00**
	CPR-1000	1 000	1 748	1 931	2 128	0.08	0.01	9.33	7.04	**29.82**	**43.72**
	AP-1000	1 250	2 302	2 542	2 802	0.10	0.01	9.33	9.28	**36.31**	**54.61**
Russia	VVER-1150	1 070	2 933	3 238	3 574	0.00	0.00	4.00	16.74/16.94	**43.49**	**68.15**
INDUSTRY CONTRIBUTION											
EPRI	APWR. ABWR	1 400	2 970	3 319	3 714	0.12	0.01	9.33	15.80	**48.23**	**72.87**
Eurelectric	EPR-1600	1 600	4 724	5 575	6 592	0.19	0.02	9.33	11.80	**59.93**	**105.84**

*The cost estimate refers to the EPR in Flamanville (EDF data) and is site-specific.

Ref: NEA/IEA (2010) Table 3.7a

Fuel Cycle Costs and O&M Costs

- O&M often given as
  - Fixed part ($ or € per kW/a)
  - Variable part ($ or € per MWh)
- But sometimes not very clear:
  - Fuel may be part of variable O&M (often in UK figures)
  - Fixed part may contain large investments (refurbishments)
  - MIT, Du & Parsons use ‘fixed”, ‘variable’ and ‘incremental capital cost’ in $ per kW/a (??) ← continuous refurbishm investments?
- No comprehensible structure from NEA/IEA (2010)

  Order of magnitude ~ **10 to 20 $$_{2008}$ per MWh**

  → generic figure ~15 $$_{2008}$ per MWh (±5 $$_{2008}$ per MWh)

Fuel Cycle Costs **and O&M Costs**

Order of magnitude ~ 10 to 20 $\$_{2008}$ per MWh

→ **generic figure ~15 $\$_{2008}$ per MWh (±5 $\$_{2008}$ per MWh)**

Or,

with 1 $\$_{2008}$ = 0.68 $€_{2008}$

and

$€_{2008} \approx €_{2012}$ (adapted nuclear S curve Europe)

Total O&M cost ~ **10.2 $€_{2012}$ per MWh_e**

Generic order of magnitude O&M cost

~ 10 $€_{2012}$ per MWh_e (± 3.5 $€_{2012}$ per MWh_e)

Table of Contents

LCOE computations

1) New Build

Parameters:

- Load Factor=85%;
- Operation Time T=60y;
- Construction Period = 6 years
- Decommissioning = 15% of OCC
- Discount Rates 5% & 10% real

LCOE computations

1) New Build

LCOE contributions Fuel cycle and O&M:

- **LCOE fuel-cycle: 6 $€_{2012}$ per MWh (± 0.75 $€_{2012}$ per MWh)**
- **LCOE O&M: 10 $€_{2012}$ per MWh (± 3.5 $€_{2012}$ per MWh)**

LCOE computations

Recall: Capital Cost Estimate of This Study - Summary OCC (EUR_{2012}/kW)

However, to accommodate the clear signal from the industrial actors, and endorsed by the ENEF Steering Committee, it makes sense for Europe, to *emphasize the high uncertainty bracket of estimate* and to attach less importance to the lower end of the uncertainty range.

This would mean that our recommended estimate for the OCC in the end is as follows:[80]

For $NOAK_2$ (5+) on a **brownfield**:	3,060...**3,400...3,910** $€_{2012}$/kW
For $FOAK_2$ **twin unit** on **brownfield**:	3,128...**3,910...5,083** $€_{2012}$/kW
For $FOAK_2$ **single unit** on **brownfield**:	3,400...**4,250...5,525** $€_{2012}$/kW

LCOE computations

5% 10%

- **Generic case**

  OCC 3,400 € (1) → LCOE(5%)= 43€/MWh & LCOE(10%)= 75€/MWh

  3,060 € (0.9) → LCOE(5%)= 41€/MWh & LCOE(10%)= 69€/MWh

  3,910 € (1.15) → LCOE(5%)= 48€/MWh & LCOE(10%)= 84€/MWh

- **FOAK$_{2}$ - twin**

  OCC 3,910 € (1) → LCOE(5%)= 48€/MWh & LCOE(10%)= 84€/MWh

  3,128 € (0.8) → LCOE(5%)= 41€/MWh & LCOE(10%)= 70€/MWh

  5,083 € (1.3) → LCOE(5%)= 57€/MWh & LCOE(10%)= 104€/MWh

- **FOAK$_{2}$- single**

  OCC 4,250 € (1) → LCOE(5%)= 50€/MWh & LCOE(10%)= 89€/MWh

  3,400 € (0.8) → LCOE(5%)= 44€/MWh & LCOE(10%)= 75€/MWh

  5,525 € (1.3) → LCOE(5%)= 61€/MWh & LCOE(10%)= 111€/MWh

All results ± 4.25 €$_{2012}$/MWh (fuel cycle and O&M)

LCOE Cost Sensitivity

Insensitive to **decommissioning cost**, **plant life > 40y**

Moderately sensitive to **fuel cost**

Highly sensitive to **interest rate, OCC**, **load factor (& construction period)**

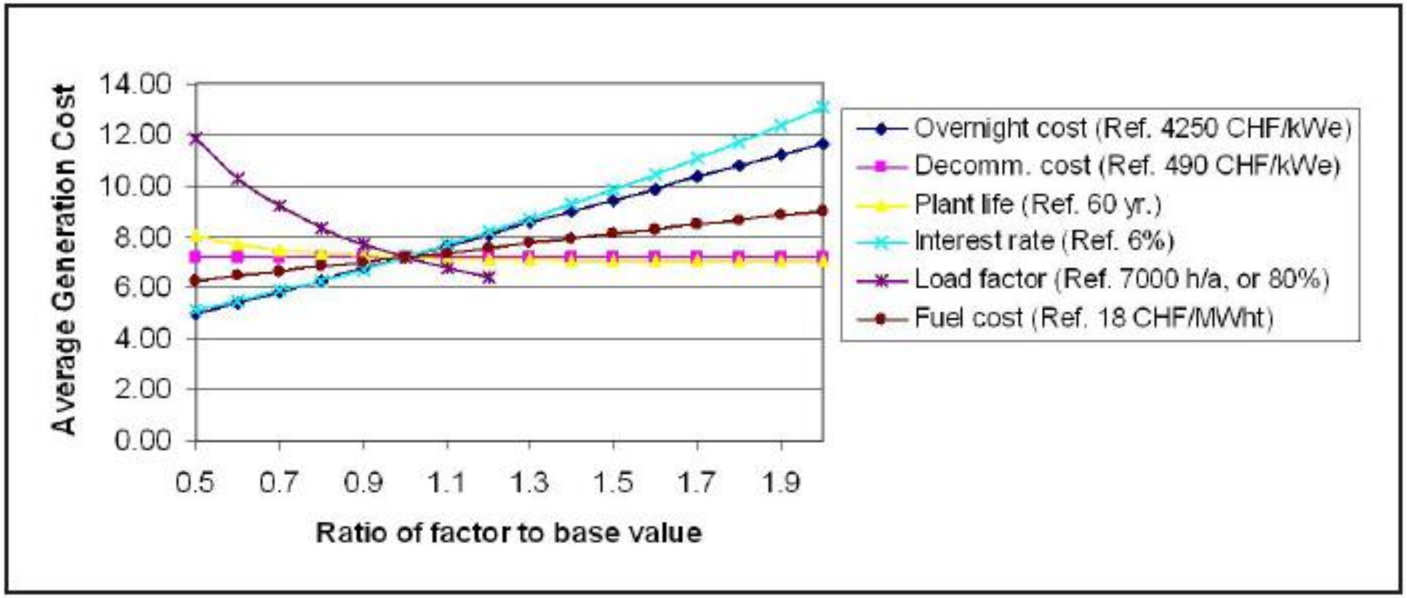


Figure 2: **Cost sensitivity for EPR.**

Ref: Hirschberg, PSI Sci Highlights, 2011

LCOE computations

2) For LTO after Refurbishment

Parameters:

- Load Factor=85%;
- Operation Time T=20y;
- Construction Period = 2-3 years
- Decommissioning = 15% of OCC Refurbishment
- Discount Rates 5% & 10% real

LCOE computations

2) For LTO after Refurbishment / Own Computations

Results:

ORC = 400 € (ref – 33%) → $LCOE_{LTO}$(5%)= 21$€_{2012}$/MWh & *$LCOE_{LTO}$(10%)= 23$€_{2012}$/MWh*

ORC = 600 € (ref) → **$LCOE_{LTO}$(5%)= 23$€_{2012}$/MWh** & ***$LCOE_{LTO}$(10%)= 26$€_{2012}$/MWh***

ORC = 850 € (ref + 42%) → $LCOE_{LTO}$(5%)= 26$€_{2012}$/MWh & *$LCOE_{LTO}$(10%)= 30$€_{2012}$/MWh*

All results ± 4.25 $€_{2012}$/MWh (fuel cycle and O&M)

Table of Contents

External Costs / Externalities

Determination of external costs & benefits to be utilized in cost/benefit analyses

Difficulties for :

- environmental externalities (release radio-isotopes)
- nuclear accidents & liabilities

→ **Value of human life**

→ **Discount factor**

External Costs / Externalities

- Some published values: **"routine operation" / no accidents**
- Again: **orders of magnitude estimates**!
  - Torfs et al. (2001, Belgium) based on ExternE (1995) methodology
    - Nuclear open fuel cycle: **0.7 €/MWh** (average; no accidents)
  - NEEDS (CEU Project, Deliv 6.1 RS1a, 2009 – p43):
    - Nuclear: **0.9-1.5 €/MWh** (depending on GHG damage – no accidents)
  - CASES (CEU Project, Deliv 6.1, 2008 – p16 & 29):
    - Nuclear: **2.1 $€_{2005}$/MWh** (status 2005-2010; no accidents)
    - Compare to hard coal (condensing plant): 31 €/MWh
  - Rabl & Rabl (2013) ~ **4.1 €/MWh**
  - IER Stuttgart (2013) ~ **3 – 3.5 €/MWh**

Summary External costs routine ~ 1 – 4 €/MWh

External Costs / Externalities

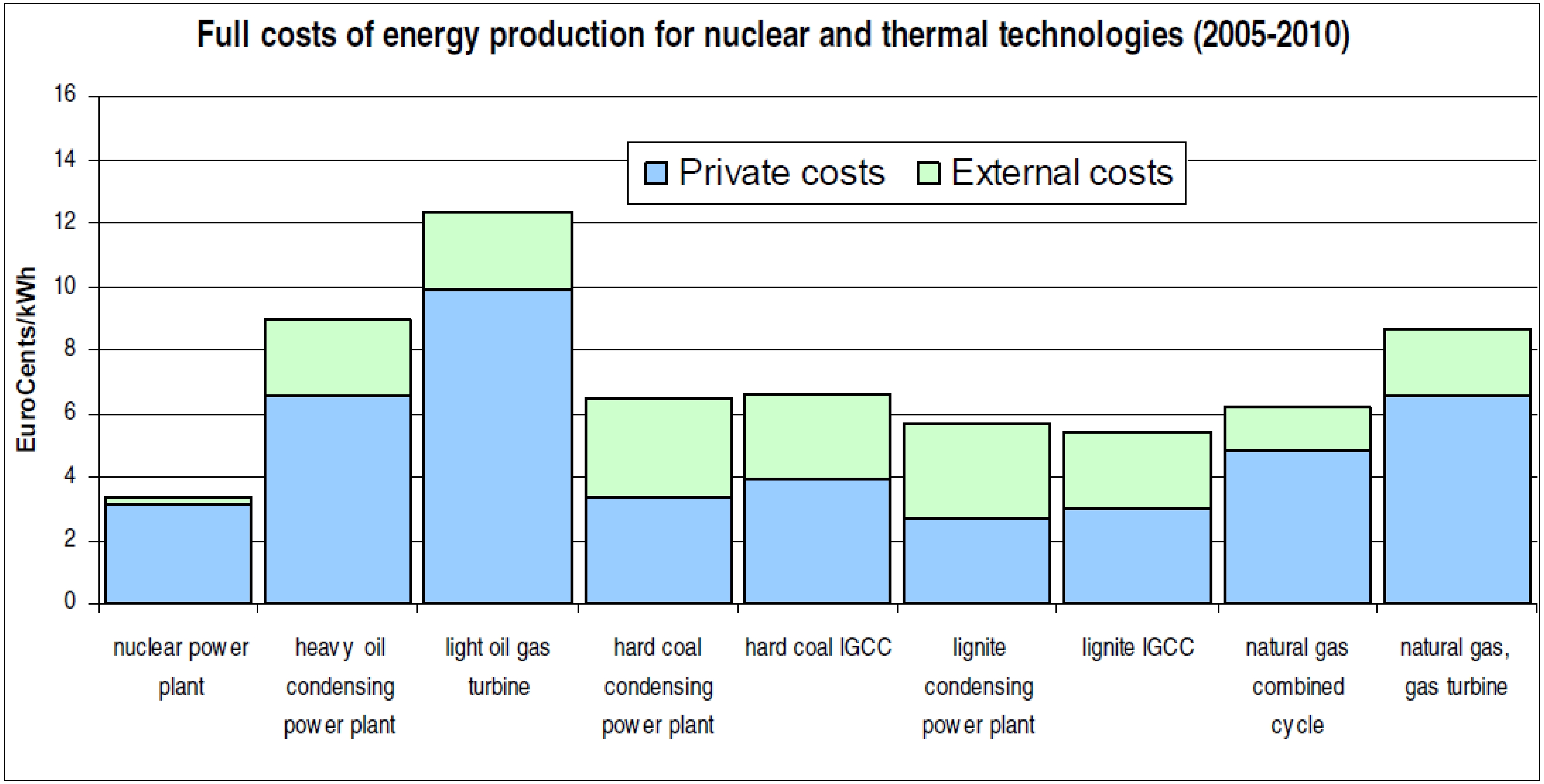
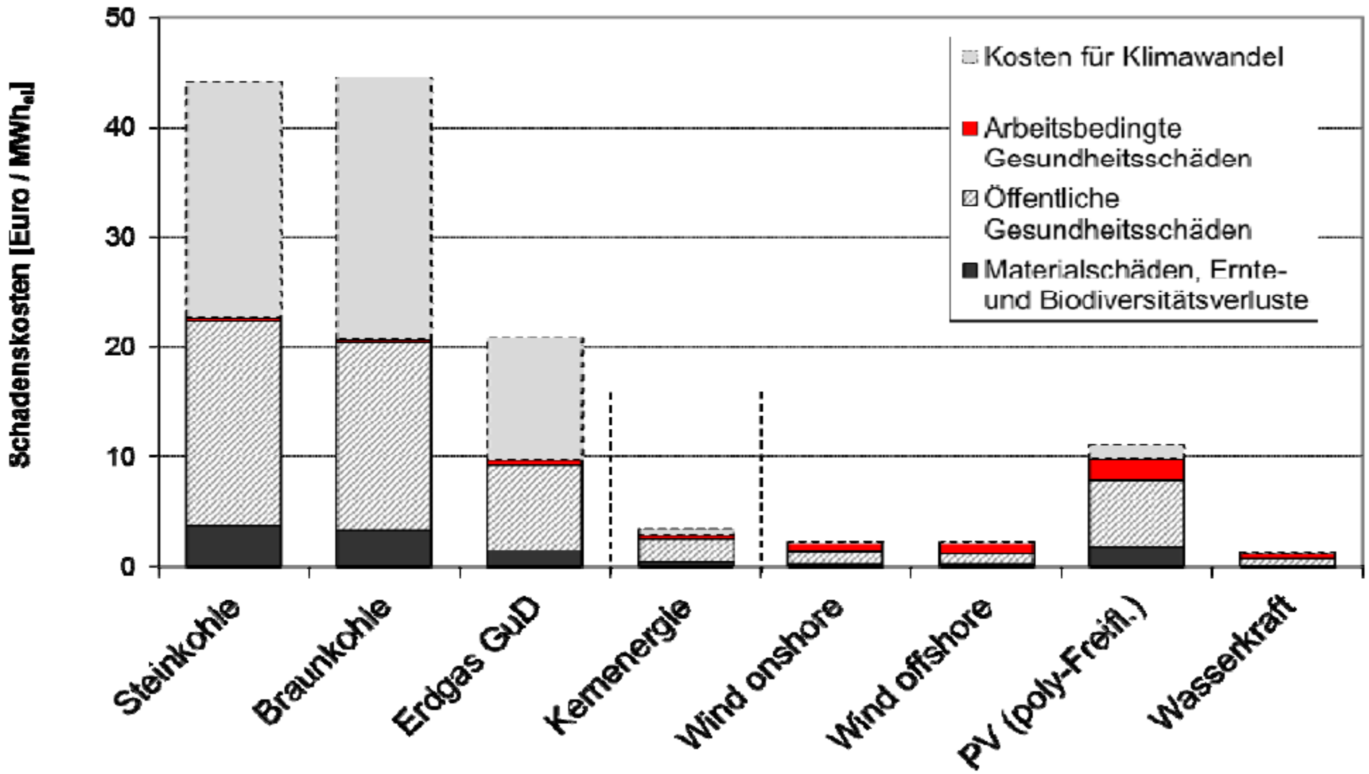


Figure 4.1 Full cost composition for nuclear and fossil fired technologies in 2005-2010

Ref: CASES, Deliverable 6.1, 2008, p 16 – **No accidents included**

External Costs / Externalities

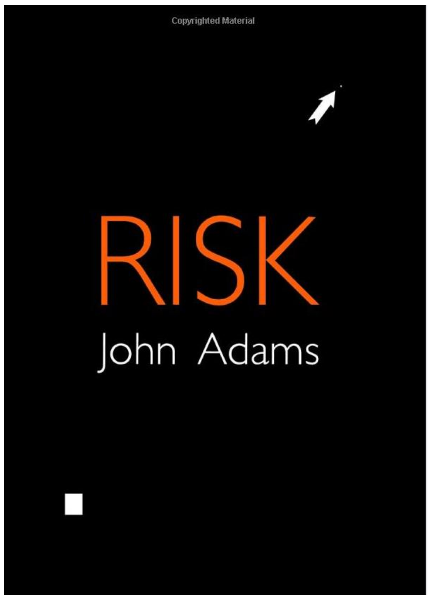


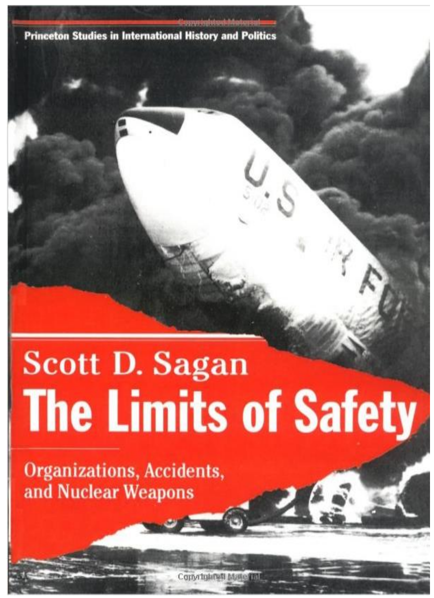
Ref: IER , Stuttgart (2013)

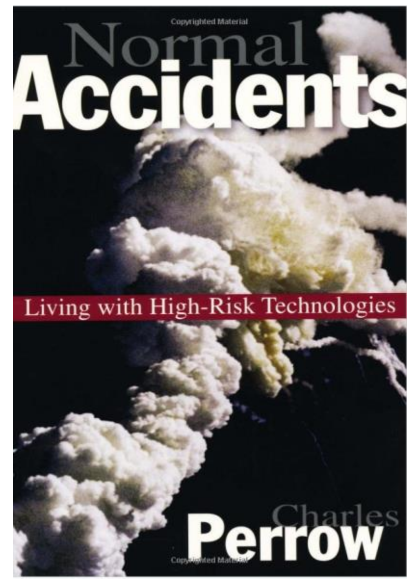
Table of Contents

Cost of Nuclear Accidents & Liability

Concept of “Risk” – sometimes controversial

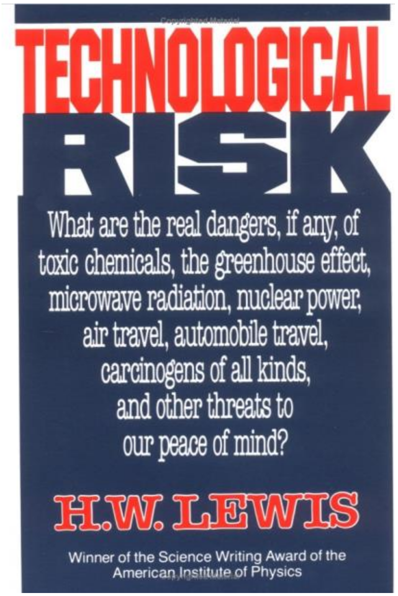


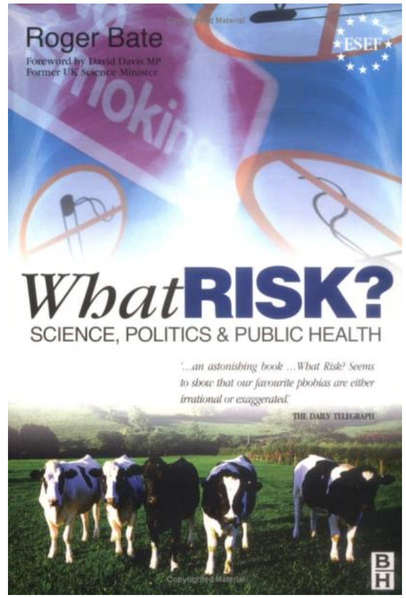


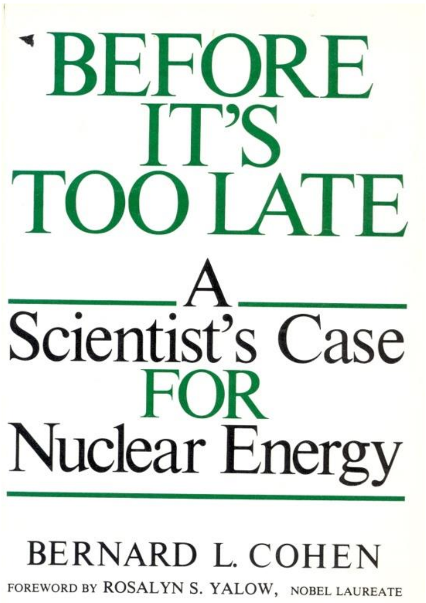


Cost of Nuclear Accidents & Liability

Issue of Risk – sometimes controversial







Cost of Nuclear Accidents & Liability

- Safety Technical Definition "Risk":

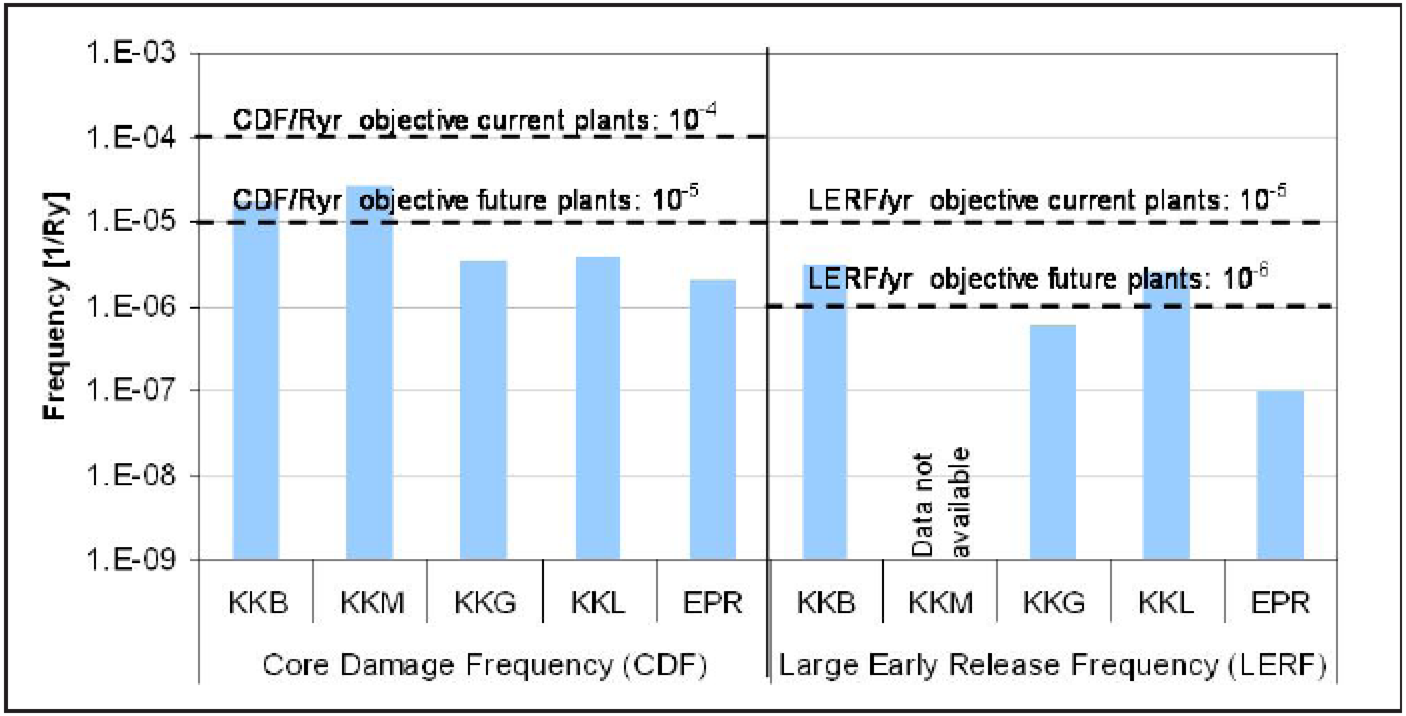
  Risk = Probability x Effect

- External cost due to a nuclear accident:

  Expected Cost = (Probability accident) x (Cost accident)

Cost of Nuclear Accidents & Liability

- Crucial element is the accident frequency



Ref: Hirschberg, PSI Sci Highlights, 2011

Cost of Nuclear Accidents & Liability

Important for **cost accident**: depends on
population density & value of land

- Estimate [NEA, 2003] ~ **0.12 €/MWh**
- Estimate [Torfs, 2001], Belgium ~ **8 x 10^{-4} – 0.35 €/MWh**
- [Rabl, 2013] 0.8…**3.8**…22.9 **€/MWh**
- [IRSN, 2007, 2012]]
  - 120...430 G€ (incl replacement energy, image FR,...)
  - With LERF ~ 10^{-5}/Ry → **0.12 – 0.43 €/MWh**
- [IER, 2013] **0.23 €/MMh**

Cost of Nuclear Accidents & Liability

- Accident frequency is theoretical estimate
- But serious accidents have happened (btwn 5 & 10 with core damage – minor and major)
- Enter **François Lévèque**, Paris Mines Tech
  1. Simplified estimate:
     - LERF EPR = 10^{-7}/react-yr → x 100 → **10^{-5}/react-a**
     - Typical damage ~100 G€ → x 10 → **10^{12} €**
     - Risk = **10 M€/react-a**
     - Production typical reactor in 1 year ~ 10 TWh/a
     - **Estimated external cost accident ~ 1 €/MWh**

Cost of Nuclear Accidents & Liability

- Enter **François Lévèque**, Paris Mines Tech
  2. Considers 'rigorous' *Bayesian* probability theory to combine theoretical predictions & "experimental results"
     - records 11 'accidents' (Cochran) → 7.8×10^{-4}/react-a
     - for theoretical prob = 6.5×10^{-5}/react-a
     - result Bayesian 'magic' → 3.2×10^{-4}/react-a
     - but (WDH): this was for 11 'accidents' and CDF, not LERF
       → result is at least factor 10 smaller → 2×10^{-5}/react-a

For damage of ~ 500 G€ and practical LERF= 2×10^{-5}/react-a,

→ **external cost accident of indeed ~1 €/MWh**

Cost of Nuclear Accidents & Liability

Summary cost Nuclear Accidents:

~ 0.3… **1** …3 **€/MWh**

Cost of Nuclear Accidents & Liability

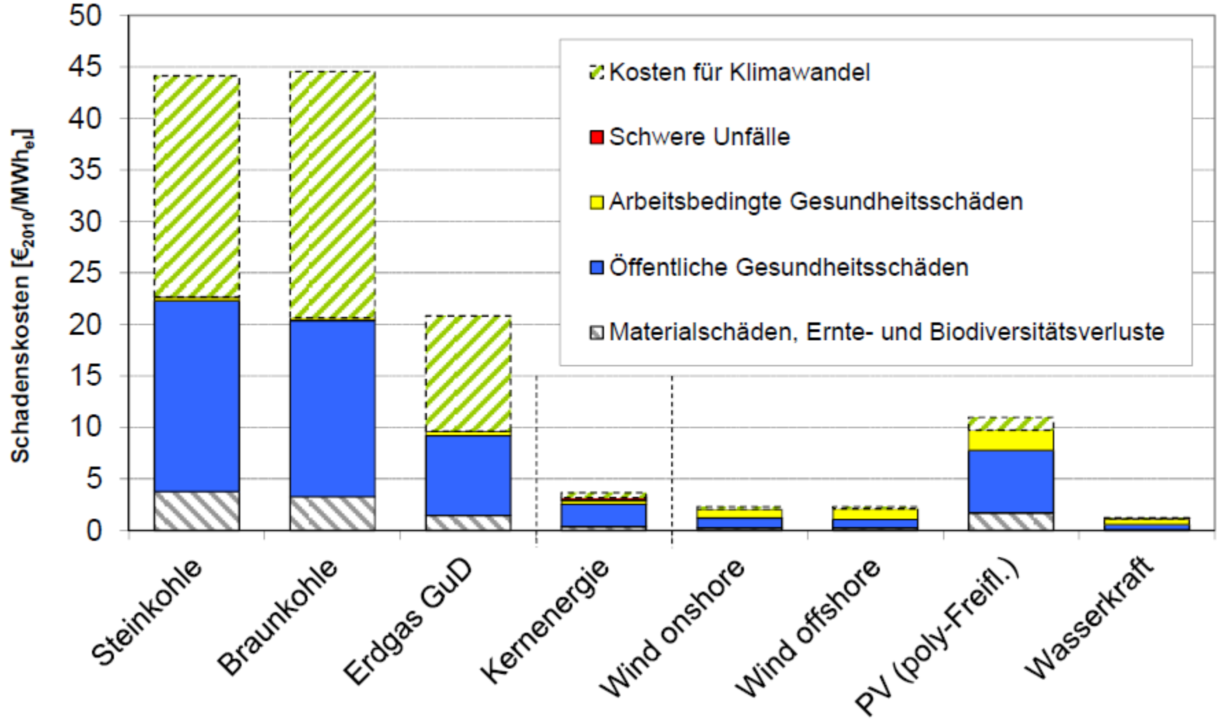


Abbildung 6: Schadenskosten der Kernenergie im Vergleich mit anderen Stromerzeugungstechnologien

Ref: [IER, 2013]

Total external cost now <u>with</u> accidents; **accidents invisible...**

Table of Contents

System Costs

- Related to integration of electricity generation plants in electricity system and liberalized market
  - NPPs & other dispatchable plants
  - RES (especially intermittent wind and PV)
- Main Ref: NEA (2012), *"Nuclear Energy and Renewables — System Effects in Low-Carbon Electricity Systems"*

  → Very valuable contribution to integration discussion!
- NPPs <u>can</u> participate in load following (FR, DE)

Table ES.1: The load following ability of dispatchable power plants in comparison

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas turbine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5%/min

Source: EC JRC, 2010 and NEA, 2011.

System Costs

Grid-Level System Cost (for 10% & 30% for each technology):

- **Nuclear: ~ 2 – 3 $\$_{2011}$/MWh**
- **Coal: ~ 1 $\$_{2011}$/MWh**
- **Gas: ~ 0.5 $\$_{2011}$/MWh**
- **Wind onsh: ~ 20 – 30 $\$_{2011}$/MWh** - outlier DE (30%) ~ 44 $\$_{2011}$/MWh
- **Wind offsh: ~ 30 – 40 $\$_{2011}$/MWh** - outlier UK (30%) ~ 45 $\$_{2011}$/MWh
- **PV: ~ 35 – 55 $\$_{2011}$/MWh** - outlier DE (30%) ~ 83 $\$_{2011}$/MWh
  - outlier UK (30%) ~ 72 $\$_{2011}$/MWh

System Costs

System Costs – simple Excel model DE

Total cost of elect supply of system a.f.o. RES penetr

Total cost of electricity supply (USD/MWh)		Reference	10% penetration level			30% penetration level		
		Conv. mix	Wind onshore	Wind offshore	Solar	Wind onshore	Wind offshore	Solar
Germany	Total cost of electricity supply	80.7	86.6	91.3	101.2	105.5	116.9	156.2
	Increase in plant-level cost	-	3.9	7.8	16.9	11.6	23.3	50.6
	Grid-level system costs	-	1.9	2.8	3.6	13.2	12.9	24.9
	Cost increase	**-**	**5.8**	**10.6**	**20.4**	**24.8**	**36.2**	**75.4**

System Costs

Total cost of elect supply of system Germany [IER, 2013]

Use of models E2M2s and JJM / self consistent analysis

Investmenst chosen by model

Four penetrations RES : 15% (only dispatchable bio & hydro)

35%; 50%; 80% in TWh

Three nuclear capacities: 20.7 GW;   0 GW   and 41.4 GW

System Costs

Total cost of elect supply of system Germany [IER, 2013]

Table 7.5: Electricity unit supply costs in EUR/MWh for considered scenarios with varying shares of renewables and varying installed capacities of nuclear power

Installed capacities of nuclear power plants/share of renewables	(EUR/MWh)		
	0 GW	20.7 GW	41.4 GW
15%	95	84	71
35%	120	109	101
50%	132	122	119
80%	174	171	174[a]

a) Variation RES-80%_NUCL-41(21LE) with one half of the nuclear power plant portfolio being entirely depreciated but retrofitted: EUR 169/kWh.

Least cost scenario RES-15%_NUCL-41 → 39 G€ (or 71 €/MWh)
Highest cost scenario RES-80_NUCL-0 → 96 G€ (or 174 €/MWh)
→Annually Δ= 57 G€ → after 20 years (even 0 discount rate) ~ 1,140 G€ with prob=1
→ after 20 years (7.5%/a) ~ 2,500 G€ with prob=1

Table of Contents

Overall Cost - Summary

LCOE New Build (rounded numbers):

- **NOAK (5+) brownfield generic single/twin**
  3,060 € (ref – 10%) → LCOE(5%)= 41$€_{2012}$/MWh & *LCOE(10%)= 69$€_{2012}$/MWh*
  3,400 € (ref) → LCOE(5%)= 43$€_{2012}$/MWh & ***LCOE(10%)= 75$€_{2012}$/MWh***
  3,910 € (ref + 15%) → LCOE(5%)= 48$€_{2012}$/MWh & *LCOE(10%)= 84$€_{2012}$/MWh*

- **$FOAK_2$ brownfield twin**
  3,128 € (ref – 20%) → LCOE(5%)= 41$€_{2012}$/MWh & *LCOE(10%)= 70$€_{2012}$/MWh*
  3,910 € (ref) → LCOE(5%)= 48$€_{2012}$/MWh & ***LCOE(10%)= 84$€_{2012}$/MWh***
  5,083 € (ref + 30%) → LCOE(5%)= 57$€_{2012}$/MWh & *LCOE(10%)= 104$€_{2012}$/MWh*

- **$FOAK_2$ brownfield single**
  3,400 € (ref – 20%) → LCOE(5%)= 43$€_{2012}$/MWh & *LCOE(10%)= 75$€_{2012}$/MWh*
  4,250 € (ref) → LCOE(5%)= 50$€_{2012}$/MWh & ***LCOE(10%)= 89$€_{2012}$/MWh***
  5,525 € (ref + 30%) → LCOE(5%)= 61$€_{2012}$/MWh & *LCOE(10%)= 111$€_{2012}$/MWh*

Uncertainty of ± 4 $€_{2012}$ / MWh

Overall Cost - Summary

LCOE LTO (rounded numbers):

- ORC = 400 € (ref – 33%) → $LCOE_{LTO}$(5%)= 21$€_{2012}$/MWh & *$LCOE_{LTO}$(10%)= 23$€_{2012}$/MWh*
- **ORC = 600 € (ref) → $LCOE_{LTO}$(5%)= 23$€_{2012}$/MWh & *$LCOE_{LTO}$(10%)= 26$€_{2012}$/MWh***
- ORC = 850 € (ref + 42%) → $LCOE_{LTO}$(5%)= 26$€_{2012}$/MWh & *$LCOE_{LTO}$(10%)= 30$€_{2012}$/MWh*

Uncertainty of ± 4 $€_{2012}$ / MWh

Overall Cost - Summary

External Costs

Without Accidents

- External costs for nuclear-generated electricity (routine): **1 – 4 €$_{2012}$/MWh**

- Compare with other means

Coal	~ 40 €$_{2012}$/MWh
Gas	~ 20 €$_{2012}$/MWh
PV	~ 10 €$_{2012}$/MWh
Wind	~ 2 €$_{2012}$/MWh

Nuclear Accidents

External cost due to nuclear accidents is ~ **0.3 … 1 … 3 €/MWh**

Overall Cost - Summary

System Costs – simple Excel model DE

Total cost of electricity supply (USD/MWh)								
		Reference	10% penetration level			30% penetration level		
		Conv. mix	Wind onshore	Wind offshore	Solar	Wind onshore	Wind offshore	Solar
Germany	Total cost of electricity supply	80.7	86.6	91.3	101.2	105.5	116.9	156.2
	Increase in plant-level cost	-	3.9	7.8	16.9	11.6	23.3	50.6
	Grid-level system costs	-	1.9	2.8	3.6	13.2	12.9	24.9
	Cost increase	-	**5.8**	**10.6**	**20.4**	**24.8**	**36.2**	**75.4**

Overall Cost - Summary

System Costs – Integrated model DE

Installed capacities of nuclear power plants/share of renewables	(EUR/MWh)		
	0 GW	20.7 GW	41.4 GW
15%	95	84	71
35%	120	109	101
50%	132	122	119
80%	174	171	174[a]

a) Variation RES-80%_NUCL-41(21LE) with one half of the nuclear power plant portfolio being entirely depreciated but retrofitted: EUR 169/kWh.

Table of Contents

Conclusion – wrap up

- **Nuclear is not cheap – but capital cost should come down (standardization, strict construction schedule,...)**
- **LTO interesting cost effective intermediate solution**
- **Back-end fuel costs low / full fuel cycle quite cheap**
- **External costs are small, including accidents**
- **System costs of nuclear are small;**
  system costs of non-dispatchable RES are very large (following refs & modeliong assumptions)

But overall, nuclear is affordable low-CO_2 electricity means!