# *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

<u>Final Report</u>

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

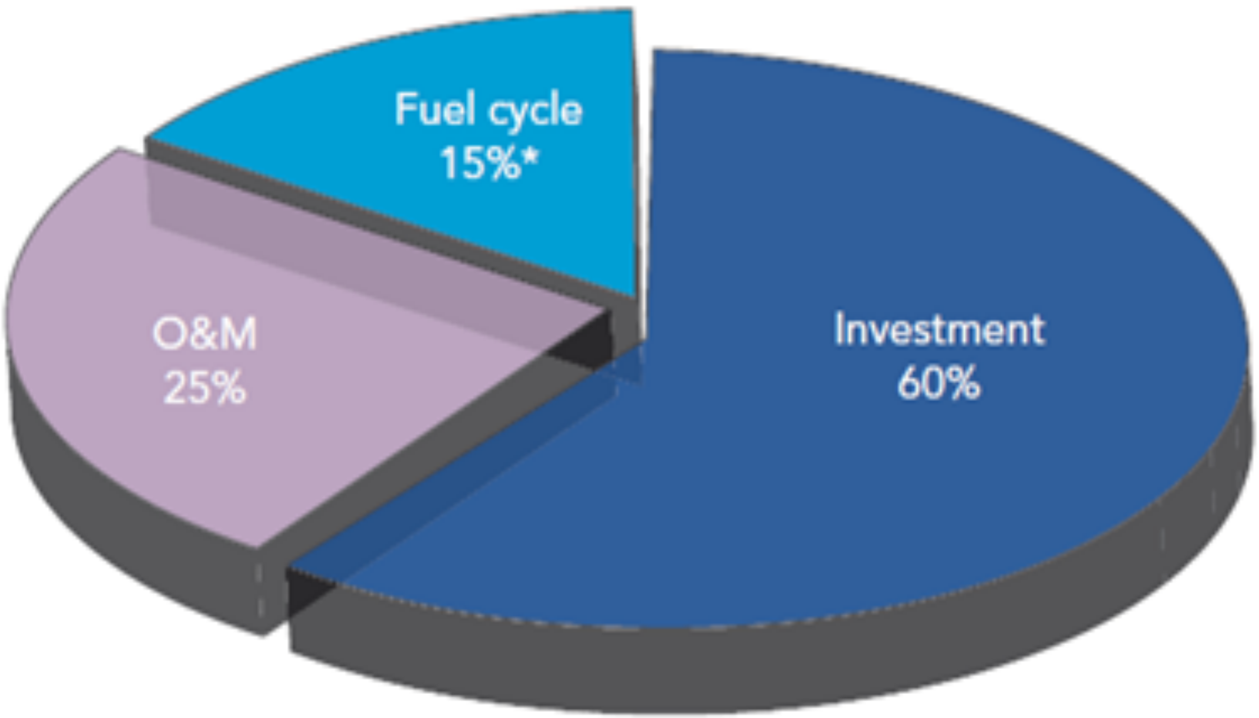
## Cost Elements of Nuclear Generation

**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

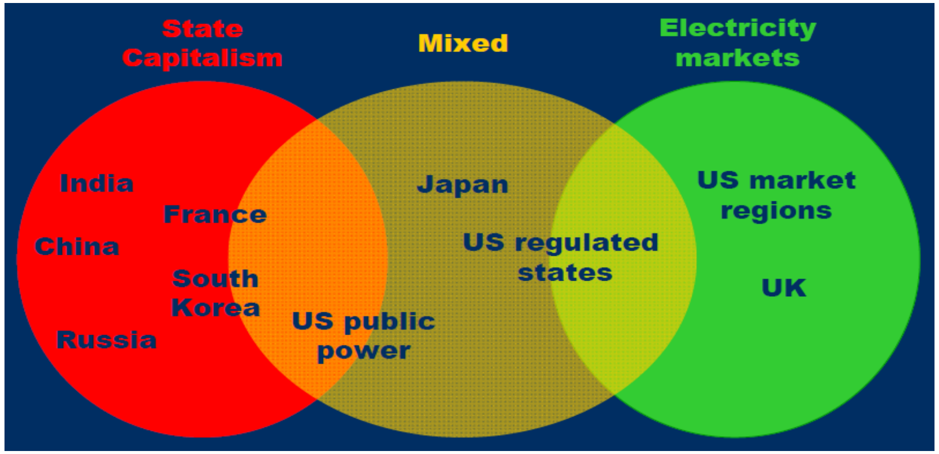
- **remaining externalities**
  - Radioactive emissions
  - Long-term waste disposal (sometimes part of fuel cycle; often already internalized)
  - Accidents – liability
  - Proliferation
  - Avoided $CO_2$ emissions – a positive externality? (Also the small amount of embedded $CO_2$ is to be considered)
  - 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

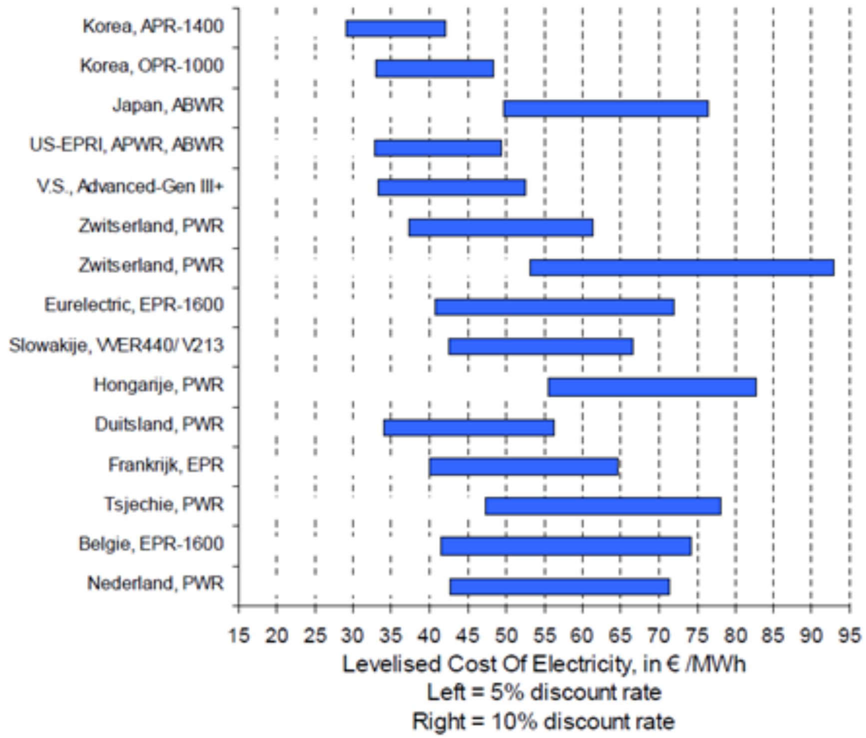
## Levelized Cost of Electricity (LCOE)

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

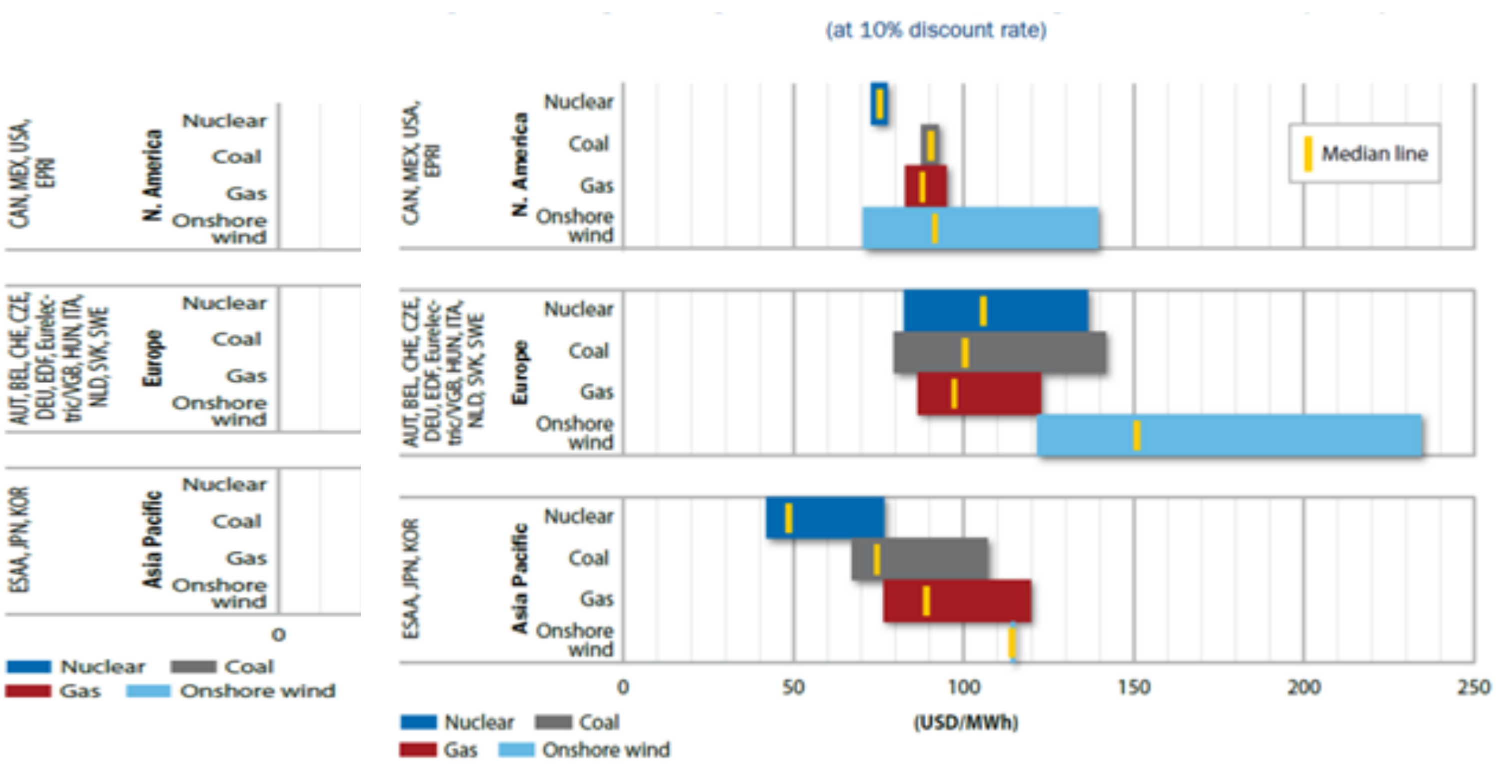
# Context & Setting the Scene

## Variation of Levelized Cost of Electricity (LCOE)

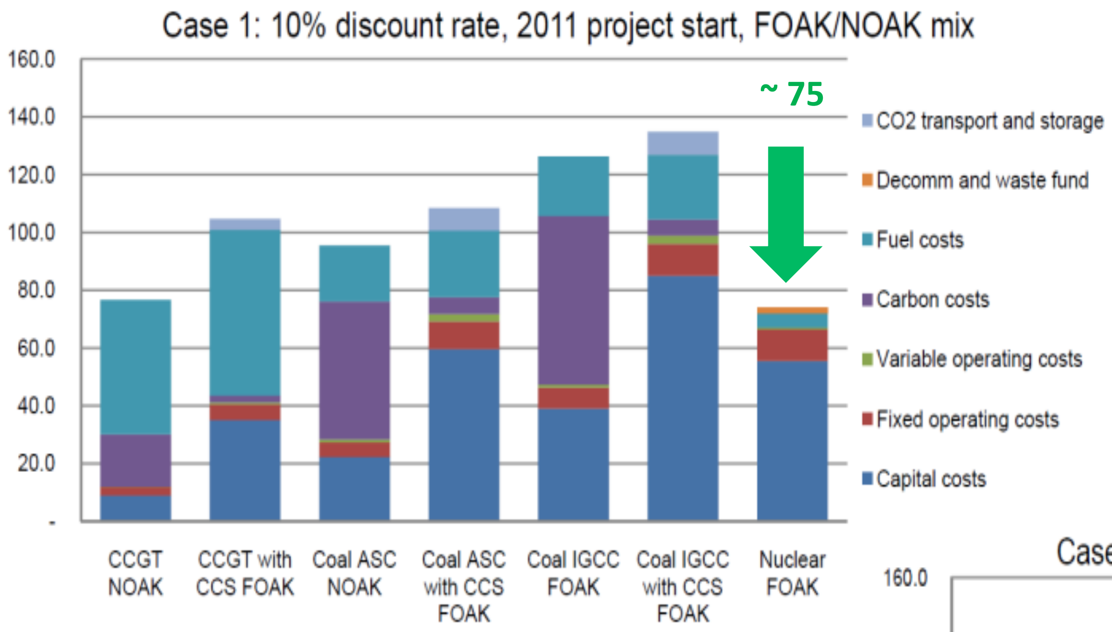


# Context & Setting the Scene

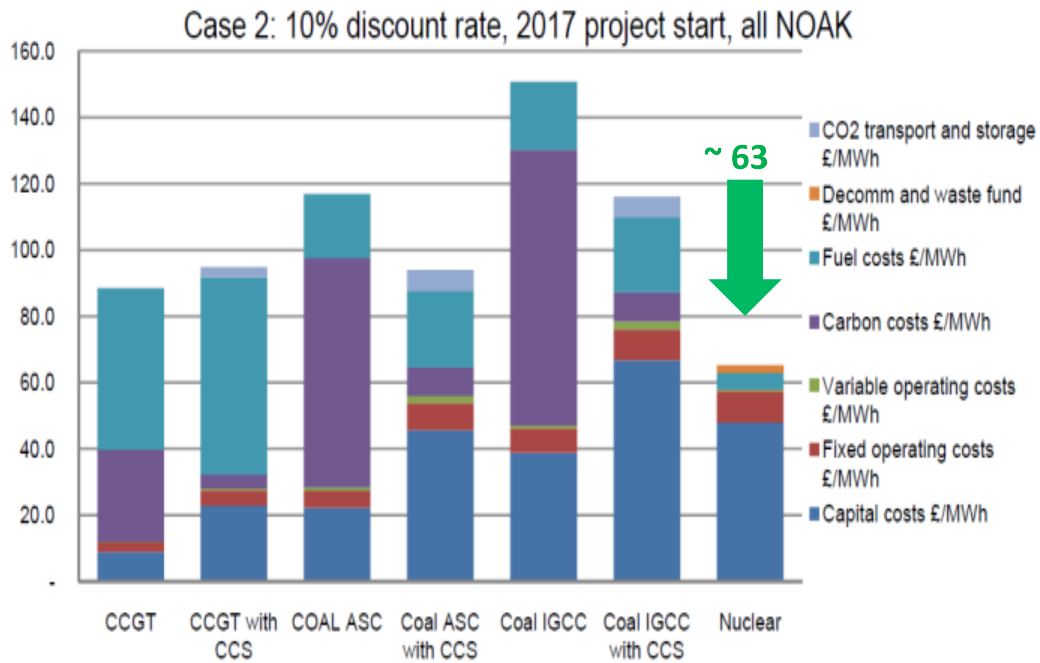
## Variation of Levelized Cost of Electricity (LCOE)



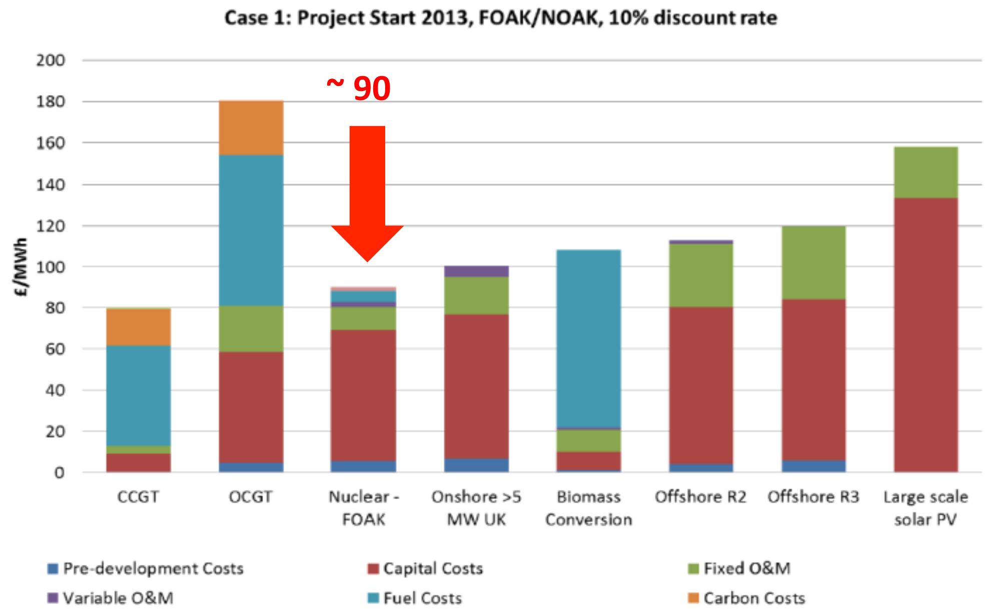
# LCOE - Illustrations



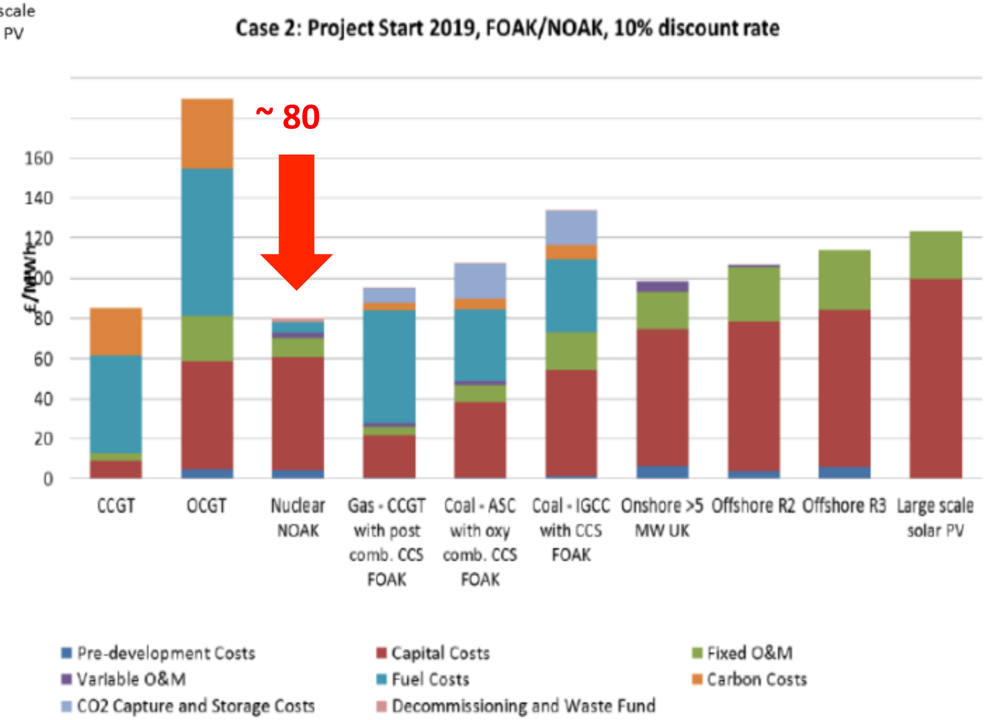

UK Figures
Parsons & Brinckerhoff **2011**
**GBP$_{2010}$/MWh**



# LCOE - Illustrations




UK Figures
Parsons & Brinckerhoff **2013**
**GBP$_{2012}$/MWh**



# Table of Contents

# Table of Contents

## Chapter 2 Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues



***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

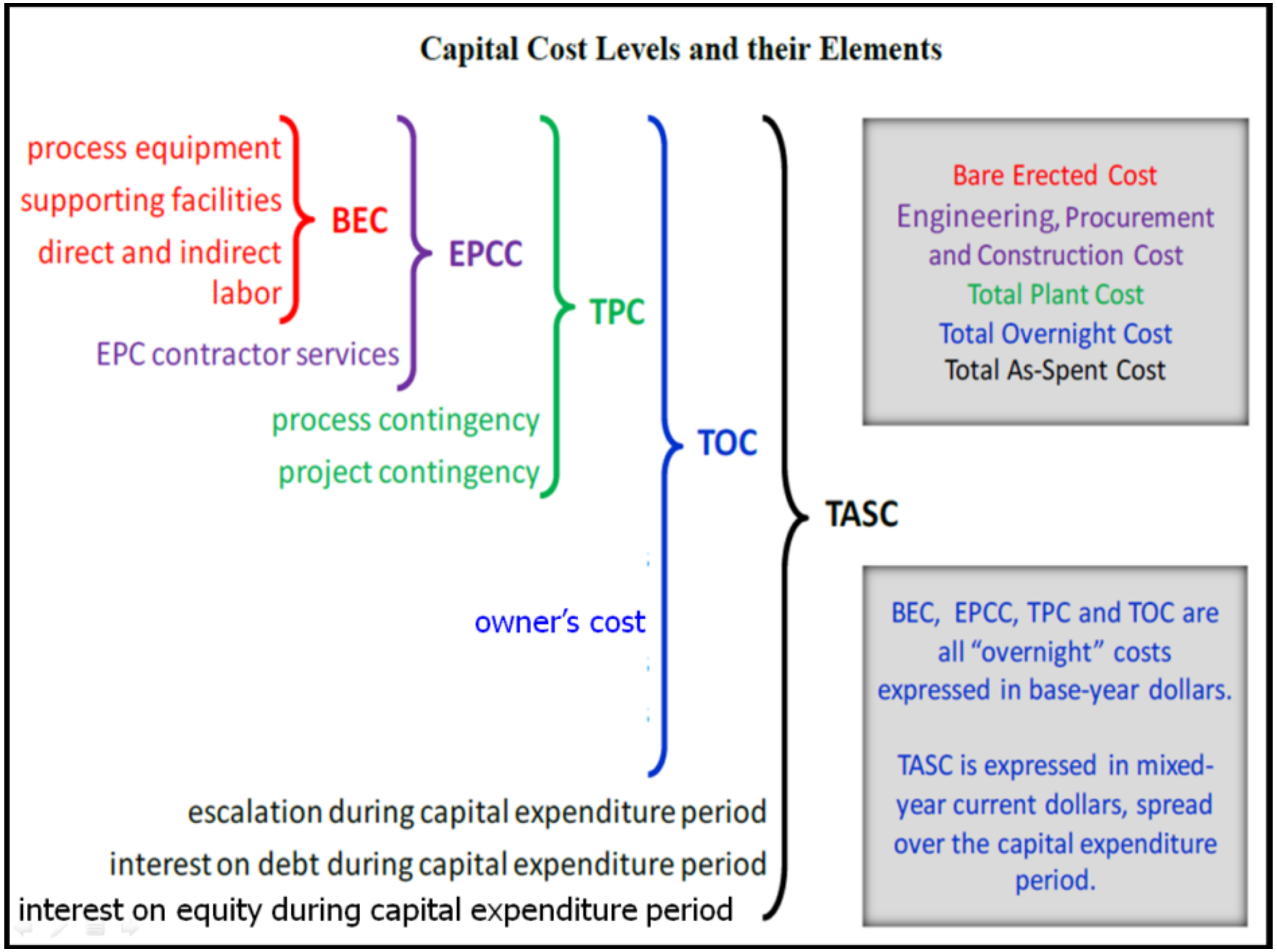
- In UK upstream/downstream separated
  - Fuel cost (upstream) ~ 11% of LCOE
  - Back-end cost ~ 3% of LCOE
  - Hence BE/(BE+Upstr) = 3/14 ~ 21% → BE ~20 of fuel-cycle cost
- In USA statutory fee of 1 $/MWh for disposal spent fuel

***To be confirmed later***

# Table of Contents

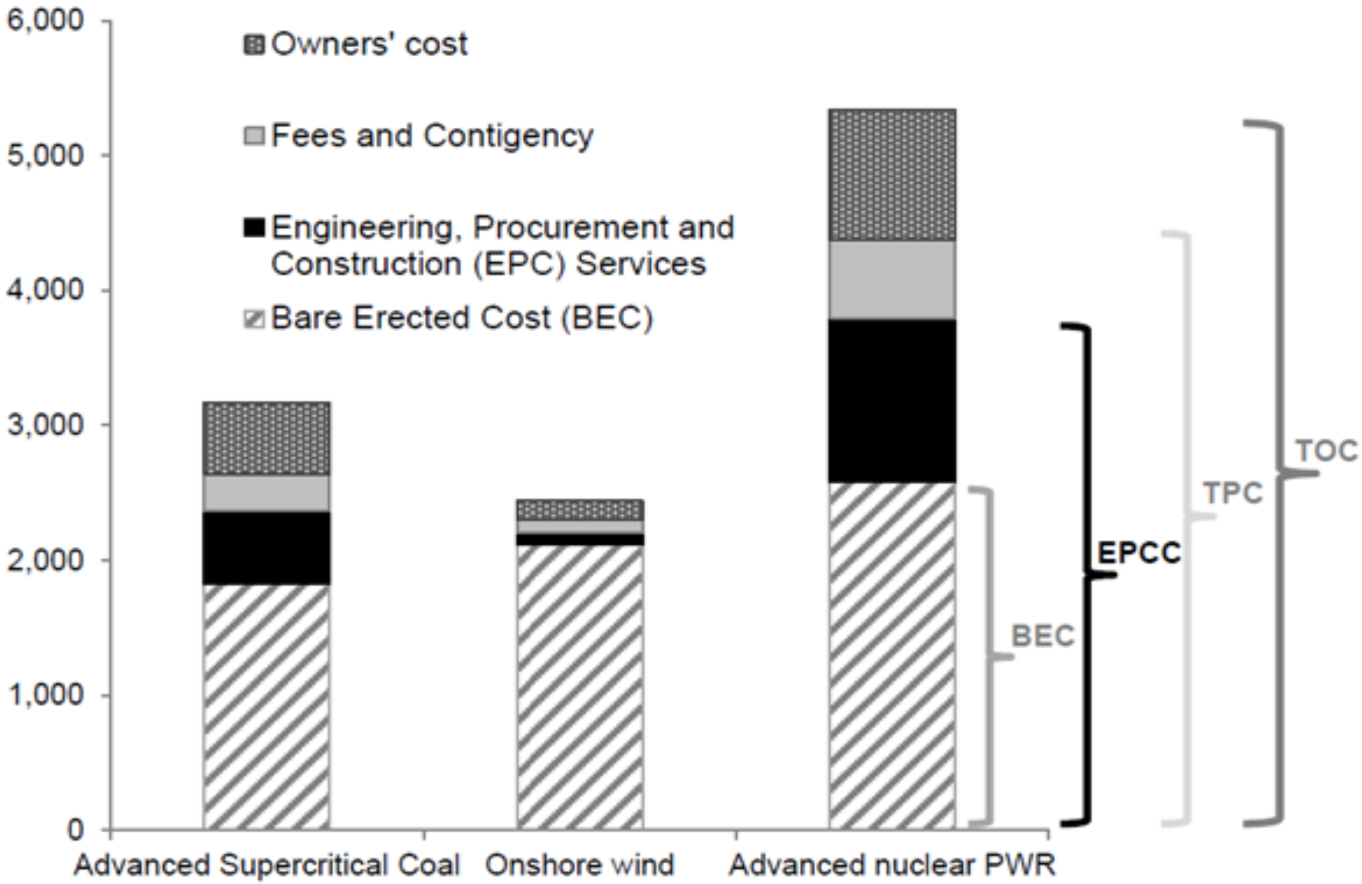
# Definitions, Conventions …

## 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

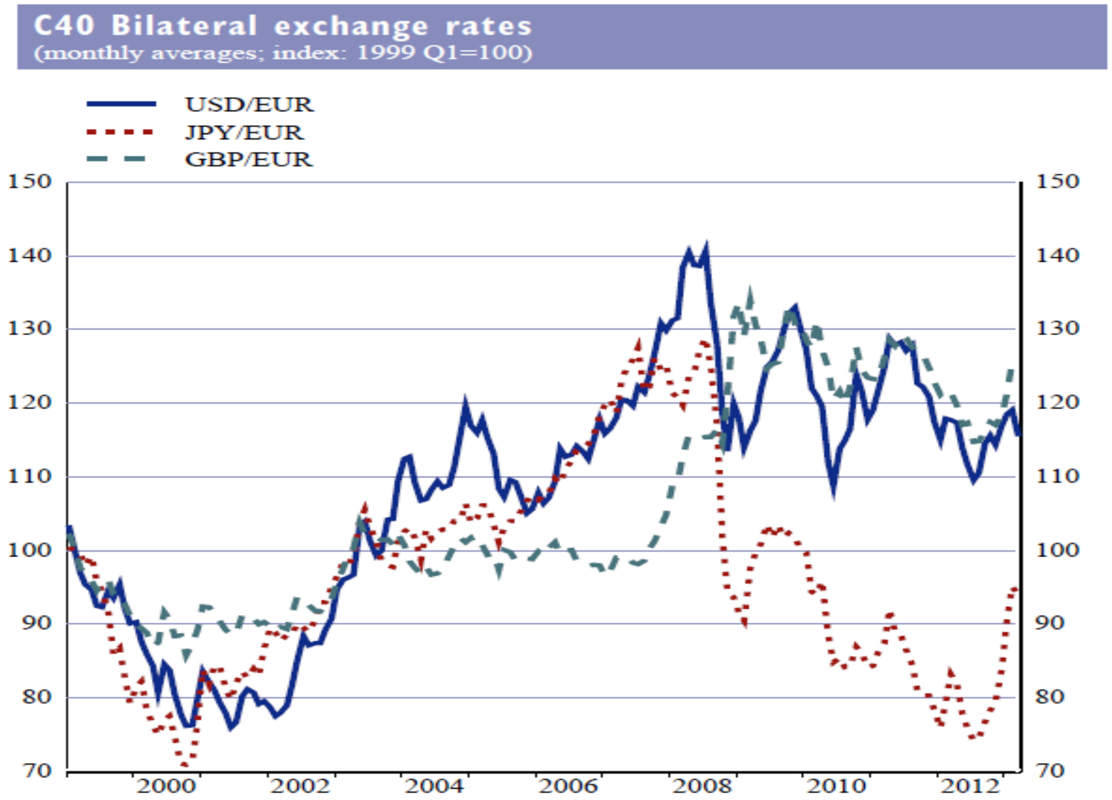
$$LCOE = P_{Electricity} = \Sigma_t((Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)^*(1+r)^{-t}) / (\Sigma_t(Electricity_t{}^*(1+r)^{-t})) \quad (2)'.$$

# 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

Must be careful with double counting !

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

*some references are unclear and/or do double counting*

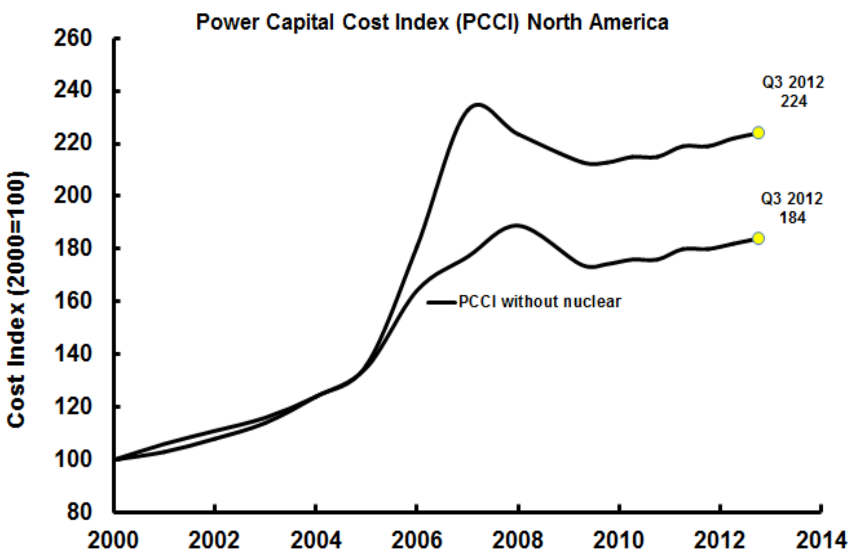
**Esc3** is ***NOT*** accepted in this work as pure "speculation"

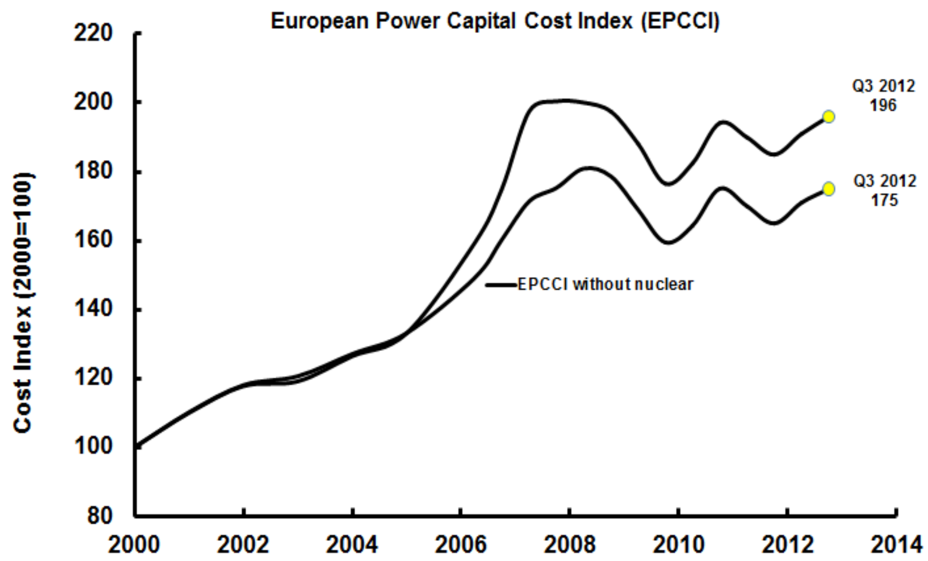
→we will define cost ranges of uncertainties, taking into account FOAK/NOAK/fleet effects

# Definitions, Conventions …

## Inflation – Escalation

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



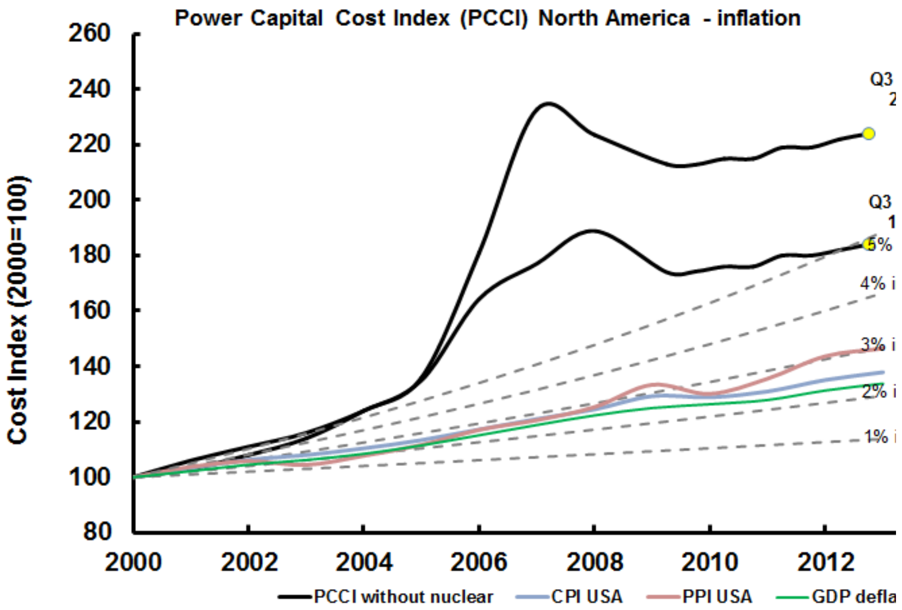



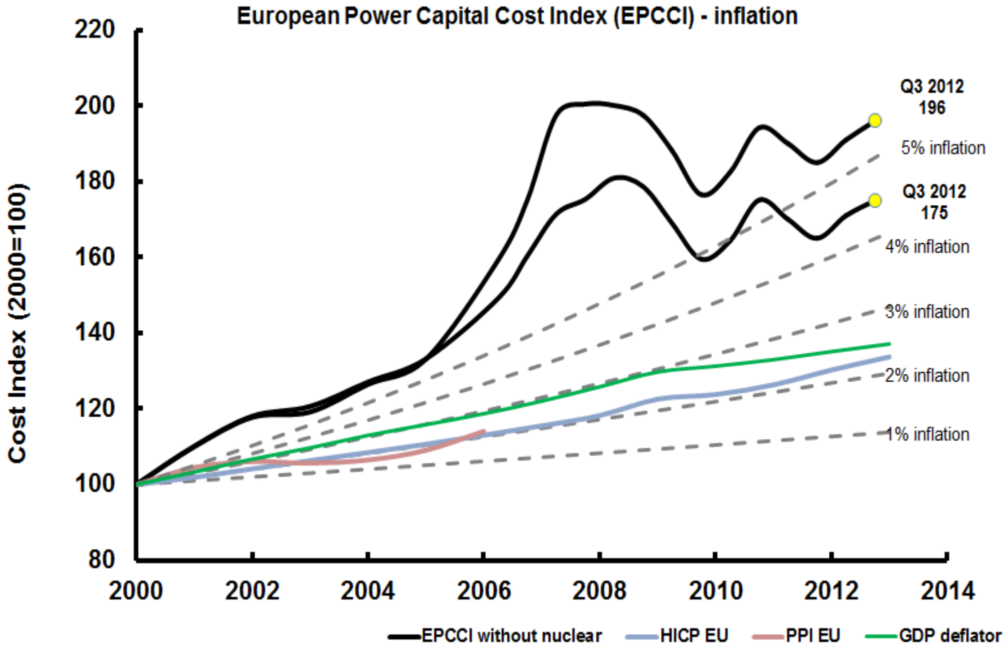

IHS CERA Power Capital Cost Indices (Esc2)

# Definitions, Conventions …

## Inflation – Escalation

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



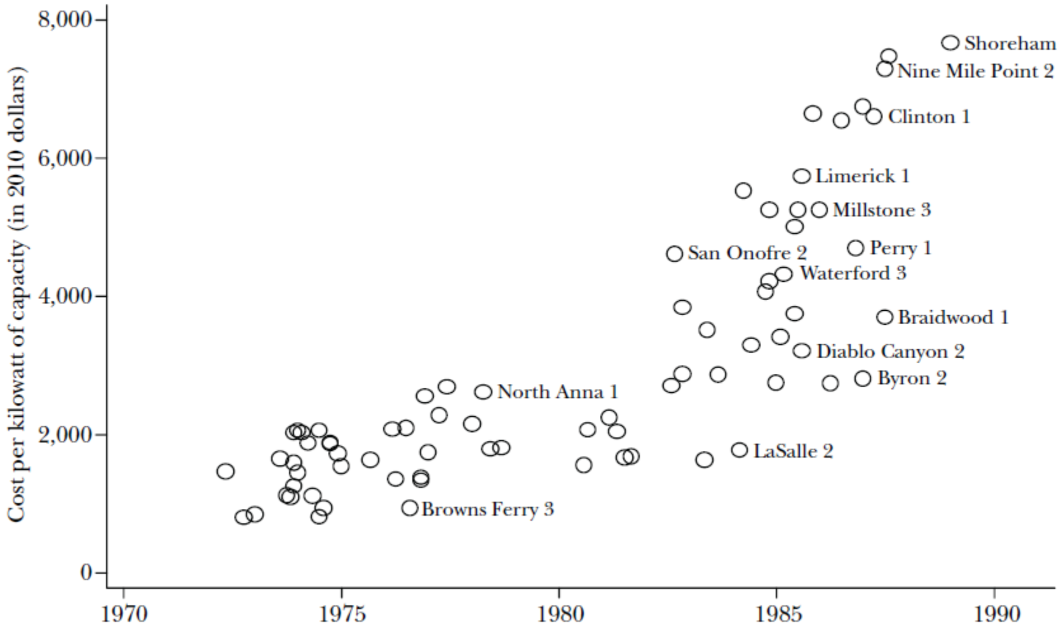

**IHS CERA Power Capital Cost Indices (Esc2) compared to usual inflation (Esc1)**

# Table of Contents

# Definitions, Conventions …

## Inflation – Escalation

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

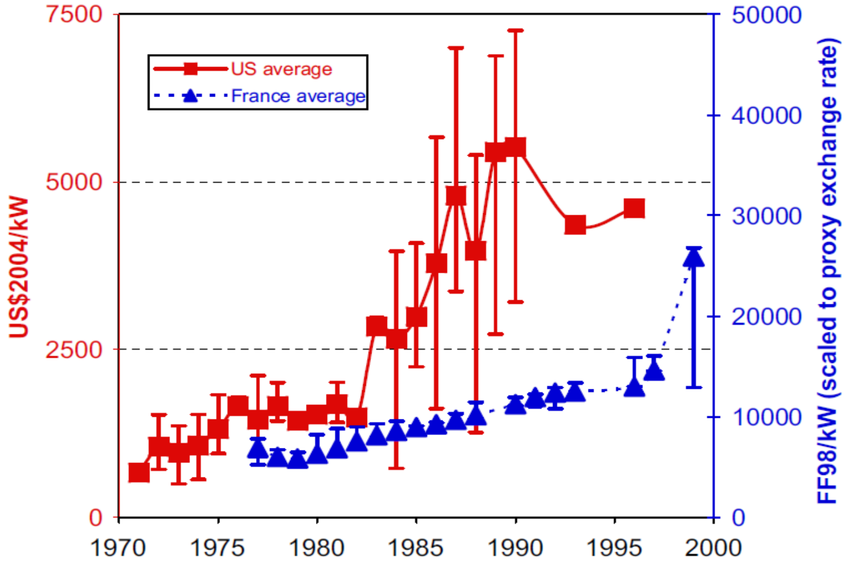


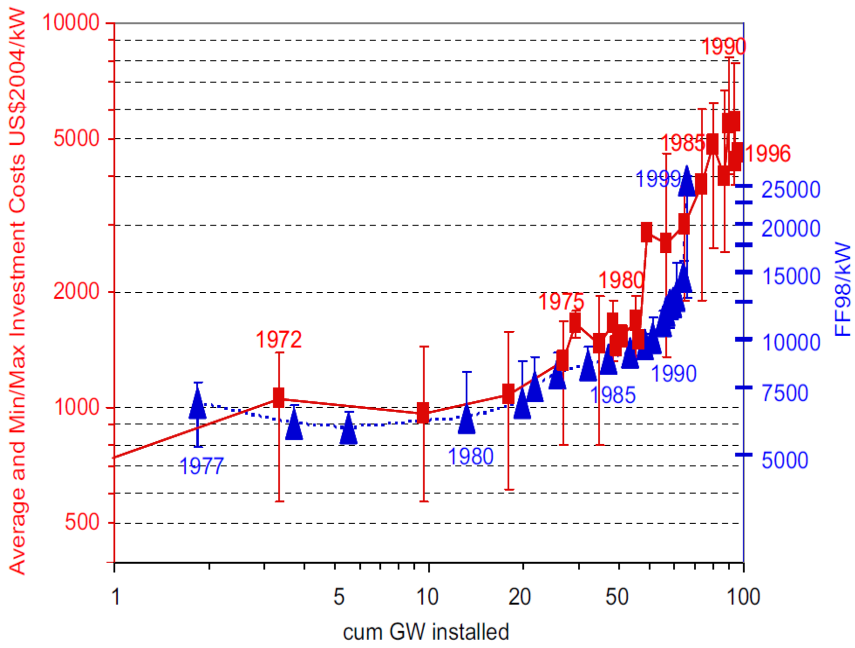

*Source:* U.S. DOE (1986), table 4.
*Notes:* Figure 3 plots "overnight" construction costs for selected U.S. nuclear power plants from the U.S. Department of Energy (1986). The figure includes *predicted* costs from the same source for a handful of reactors that were under construction but not yet in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

# Definitions, Conventions …

## Inflation – Escalation

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



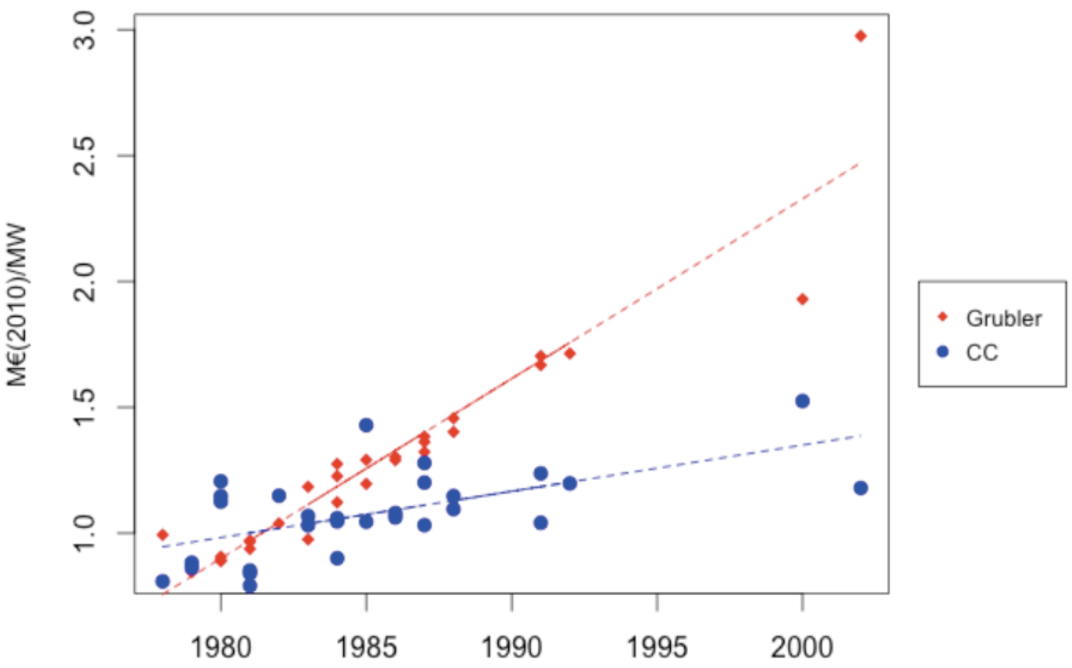

Grubler, Energy Policy 2010

# 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**

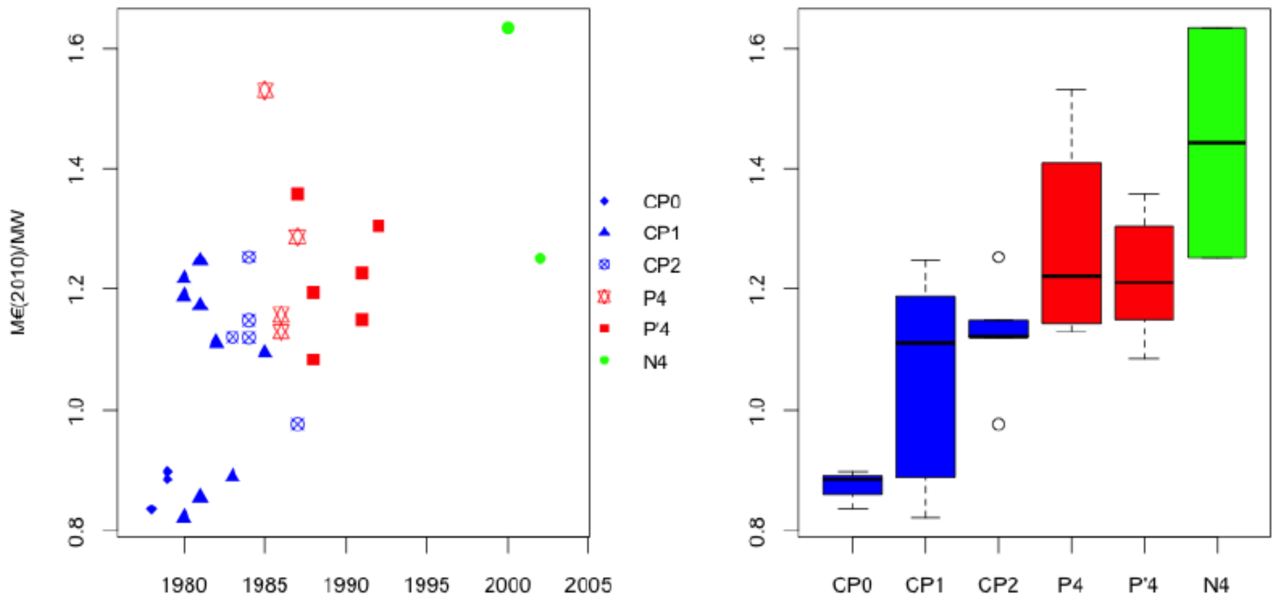
**Escalation Lévêque: 3.8%/a**

# 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

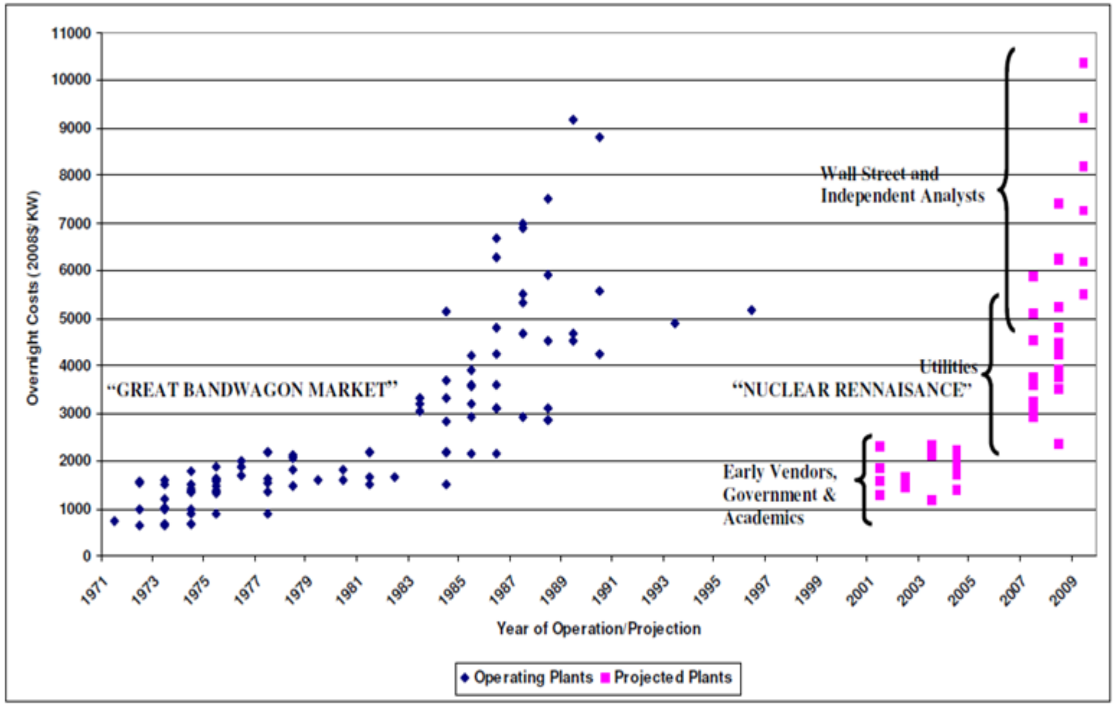
## Learning Effects / Fleet Effect

Current construction costs
Olkiluoto3 and Flamanvile

cost-estimate increases in USA
(MIT/Uchicago)

***not encouraging***

***Leads to figures like →***



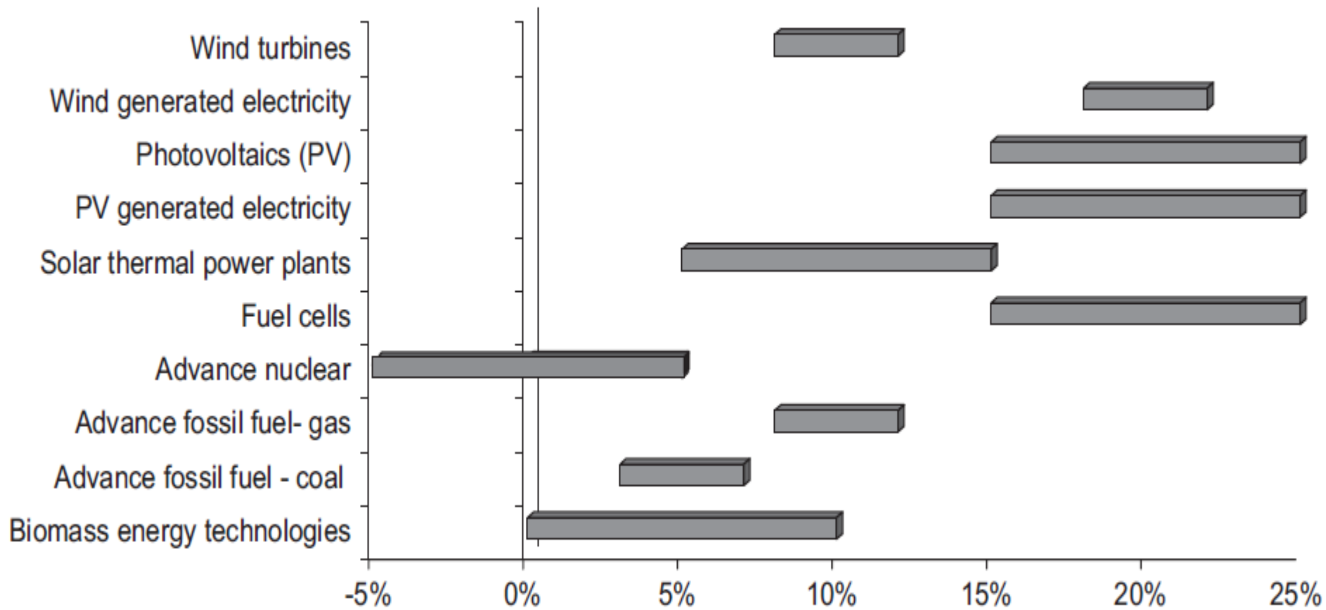

Sources: Koomey and Hultman, 2007, Data Appendix; University of Chicago 2004, p. S-2, p. S-8; University of Chicago estimate, MIT, 2003, p. 42; Tennessee Valley Authority, 2005, p. I-7; Klein, p. 14; Keystone Center, 2007, p.42; Kaplan, 2008 Appendix B for utility estimates, p. 39; Harding, 2007, p. 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)

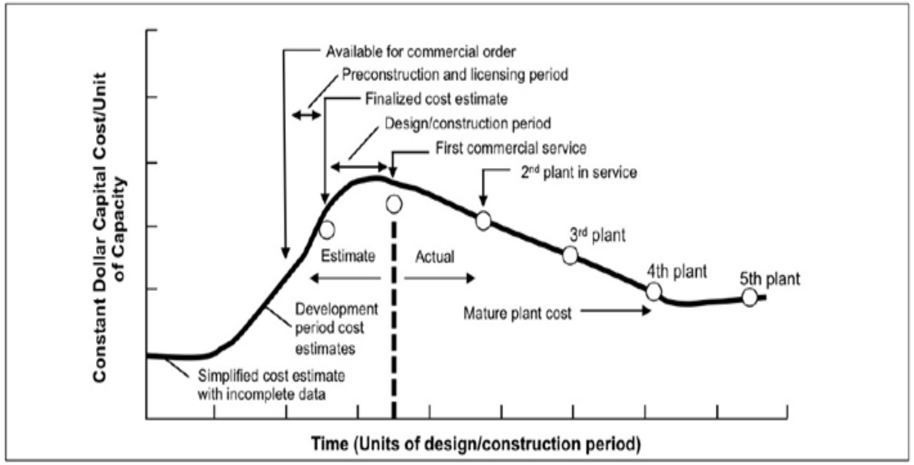
- **NOAK**: "routine construction" as of the 5-th or 6-th reactor of the same type in the same country : denoted by **$NOAK_2$ (5+)** or **$NOAK_2$ (6+)**

- 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.

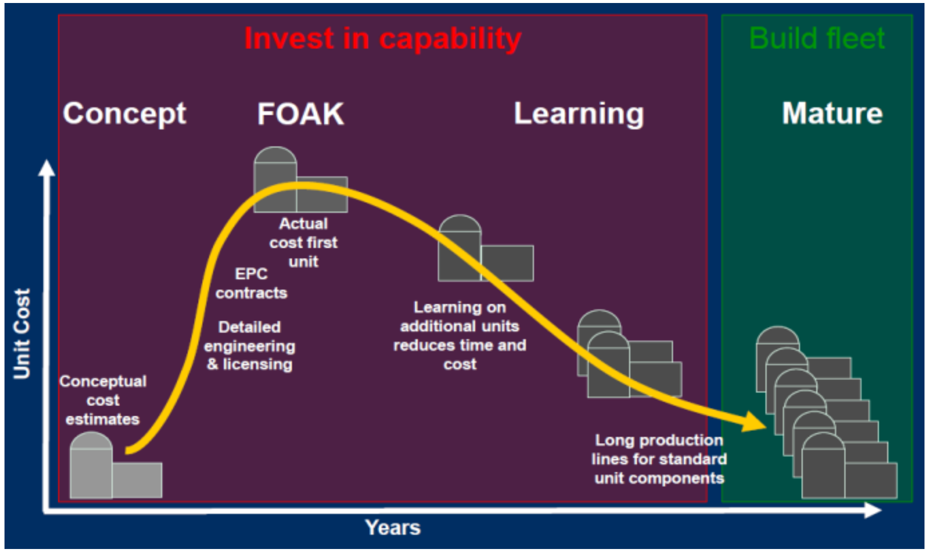
# Definitions, Conventions …

## 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.

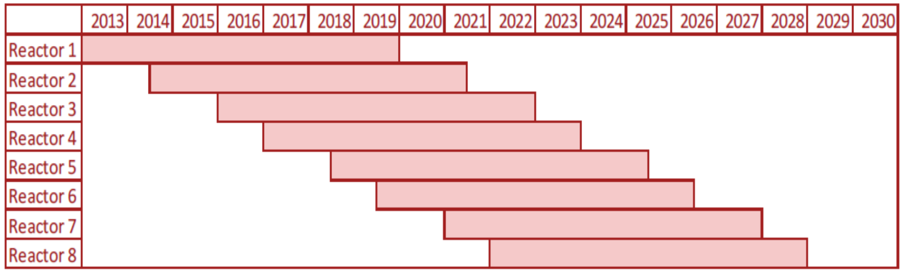
  For further cost reductions up to 30%-35% for NOAK-type of plants, it will *«require that the construction process in the future moves away from current substantial requirement for onsite labour, through better logistics control and/or increased reliance on offsite modular assembly.»*

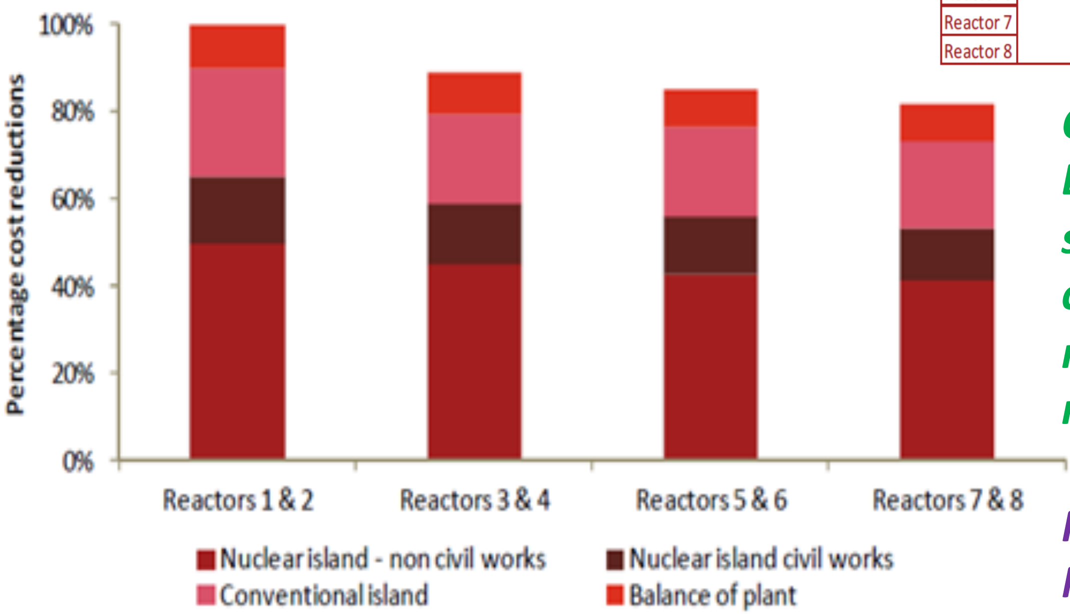
# Definitions, Conventions …

## 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.*

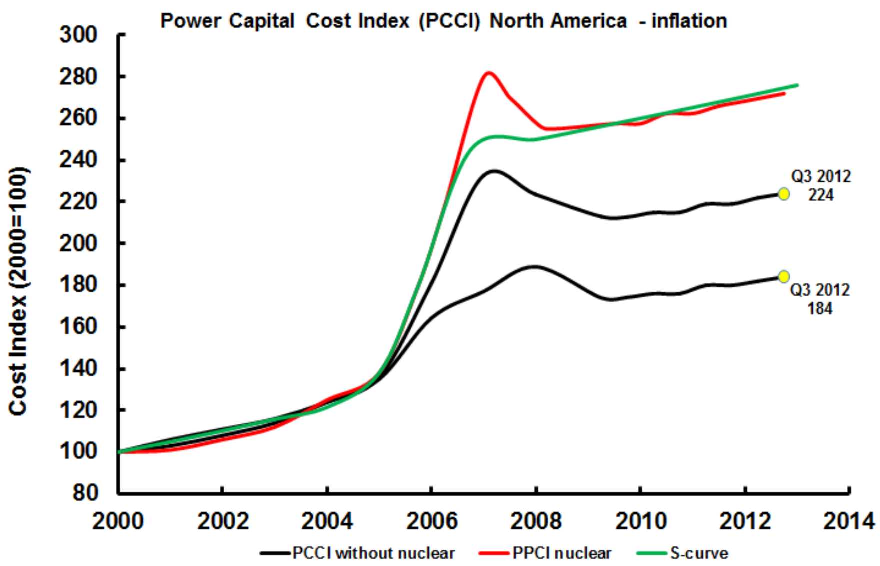
*Mott MacDonald (2010) mentions NOAK/FOAK2 reduction by ~ 25%*

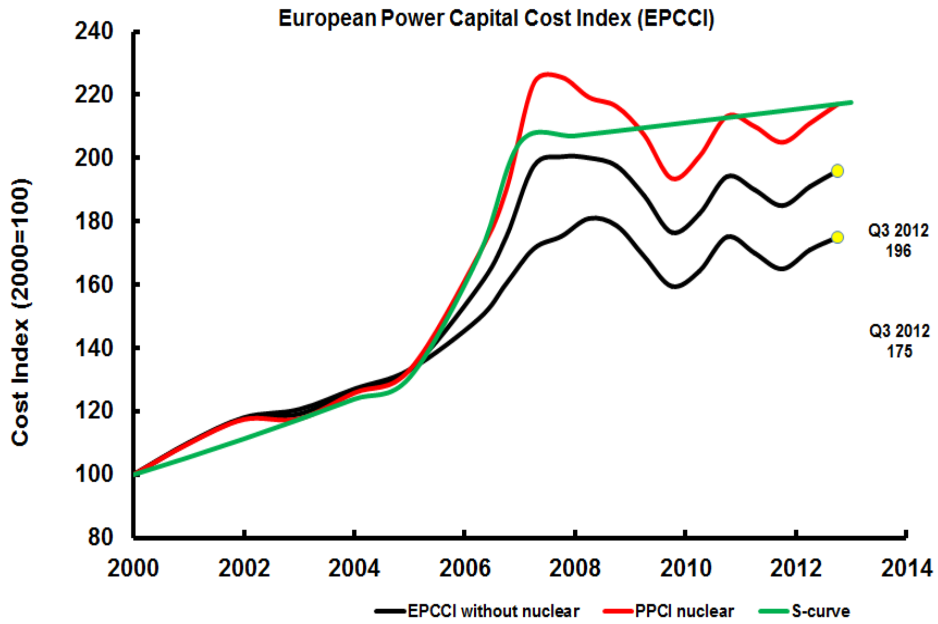
# Table of Contents

# 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

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

with

$r_{debt}$ = interest rate on debt

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

$V$ = total Volume of capital to be covered

$D$ = amount of Debt

$E$ = amount of Equity

$t_c$ = 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 private investors; for NPPs in liberalized markets discount rate penalty of ~3%-pt**

**For public 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%<br>H: +30% to +100% | 1 |
| **Class 4** | 1% to 15% | Study or Feasibility | Equipment Factored or Parametric Models | L: -15% to -30%<br>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%<br>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%<br>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%<br>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:

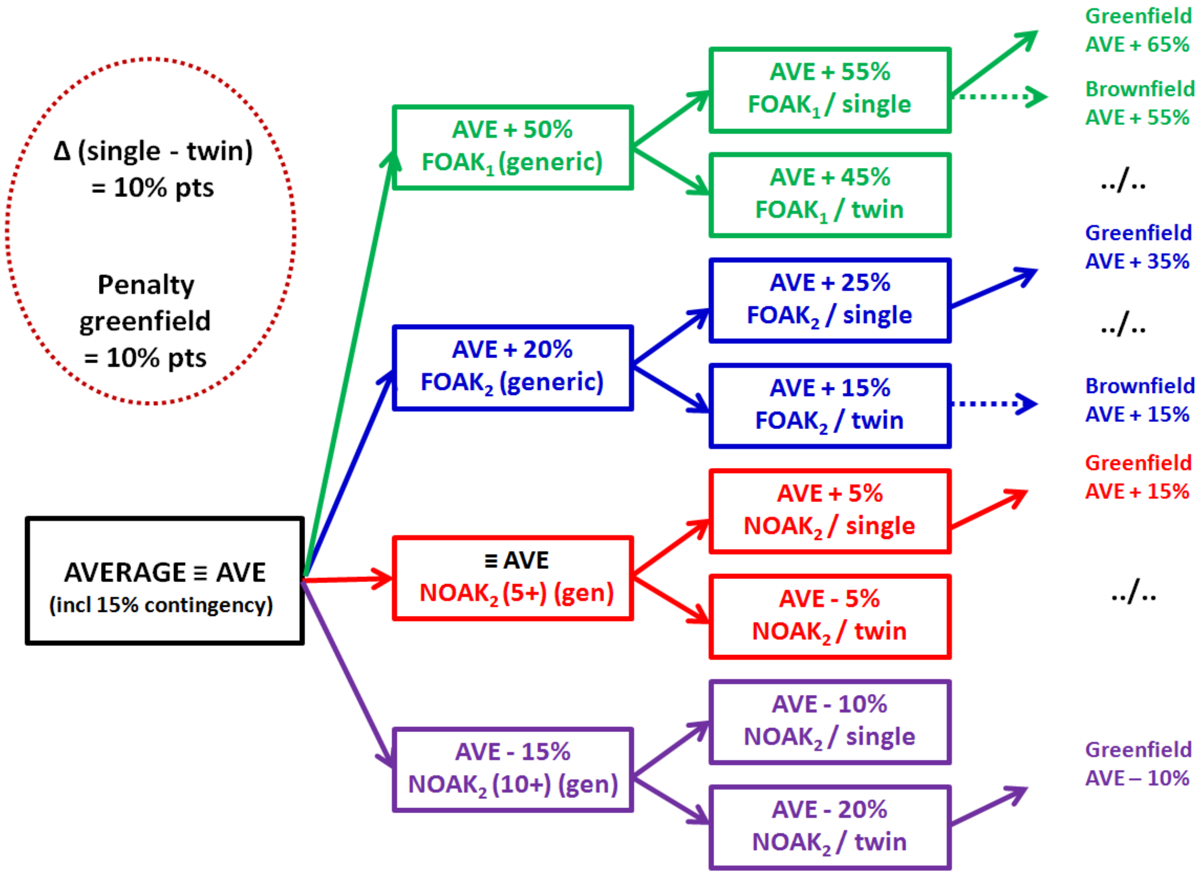
- **$FOAK_1$** contingency 30-50% (but not relevant to our report);
- **$FOAK_2$** contingency 15-30% (depending on the country; the low end would be if it concerns the 10-th plant ever of that type, the high end as long as no more than e.g., 5 units of that type have been built);
- **$NOAK_2$(10+)**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



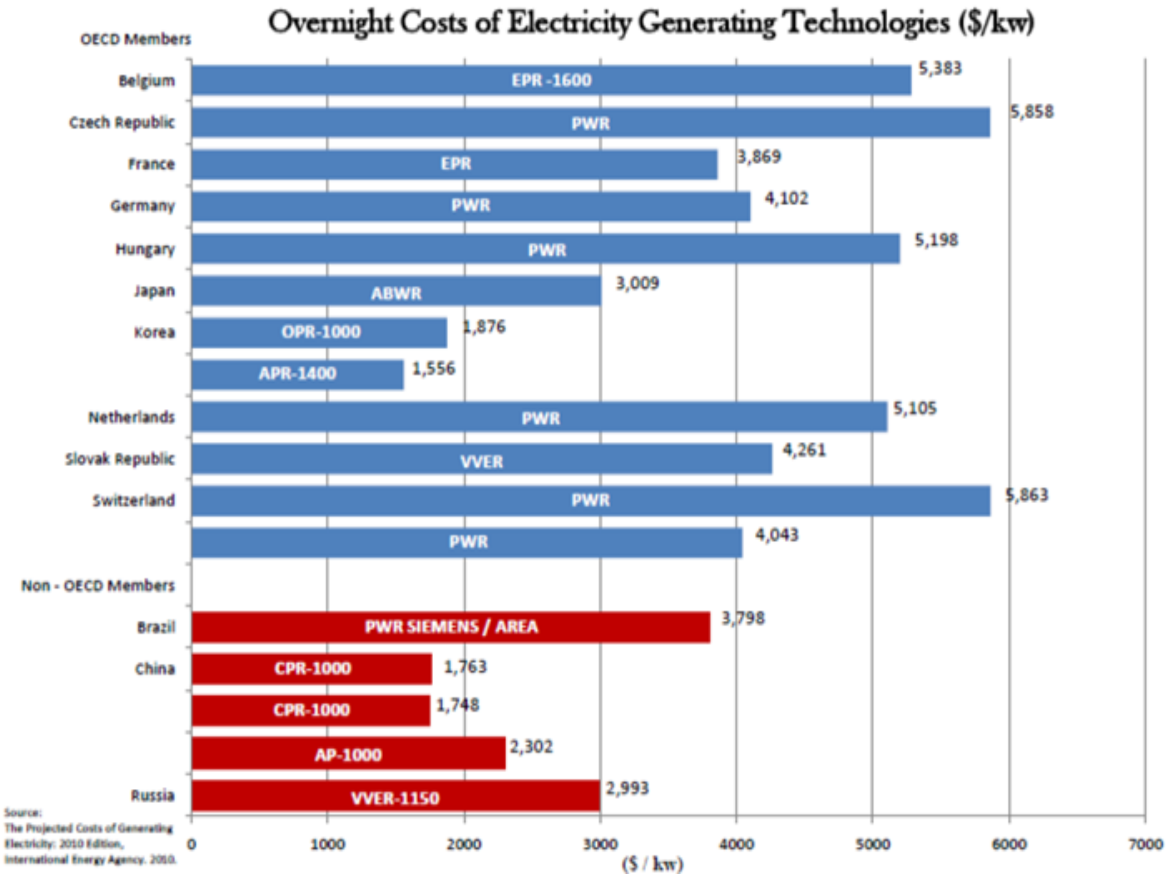
***First attempt to converge on Overnight Capital Construction Cost***

# Table of Contents

## Chapter 3 Investment Cost of New NPPs

# 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

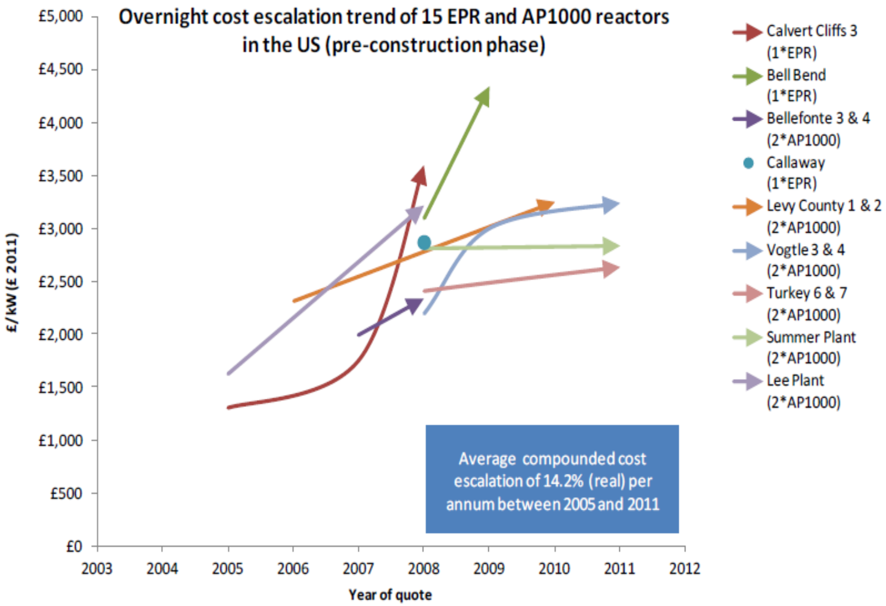


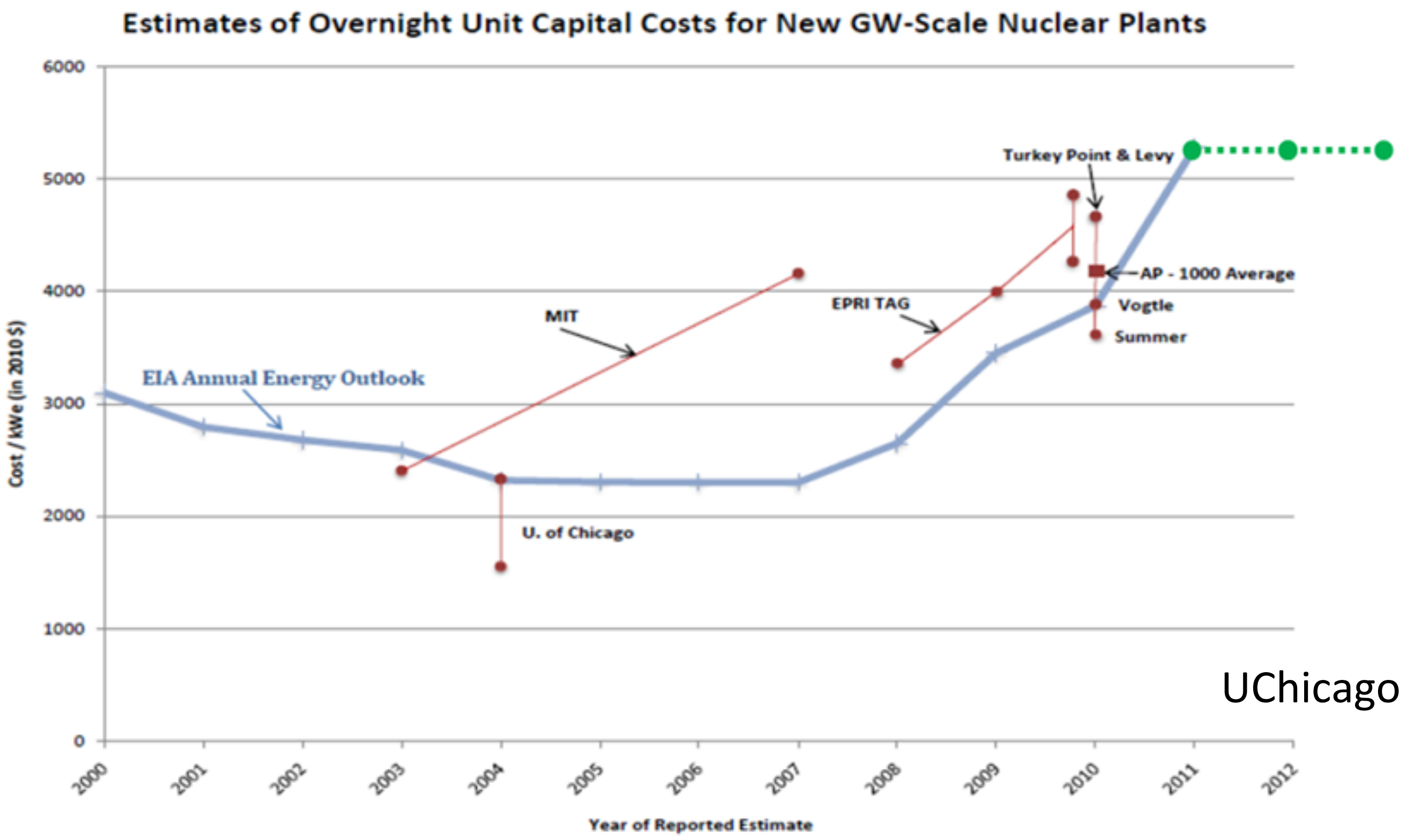

Figure 3: Overnight cost escalations in the pre-construction phase of US reactors between 2005 and 2011 (EPR and AP1000 reactor types only). All costs are expressed in 2011 values using the US CPI to index historic costs. For the Bell Bend and Callaway plants, where pure overnight cost estimates were 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

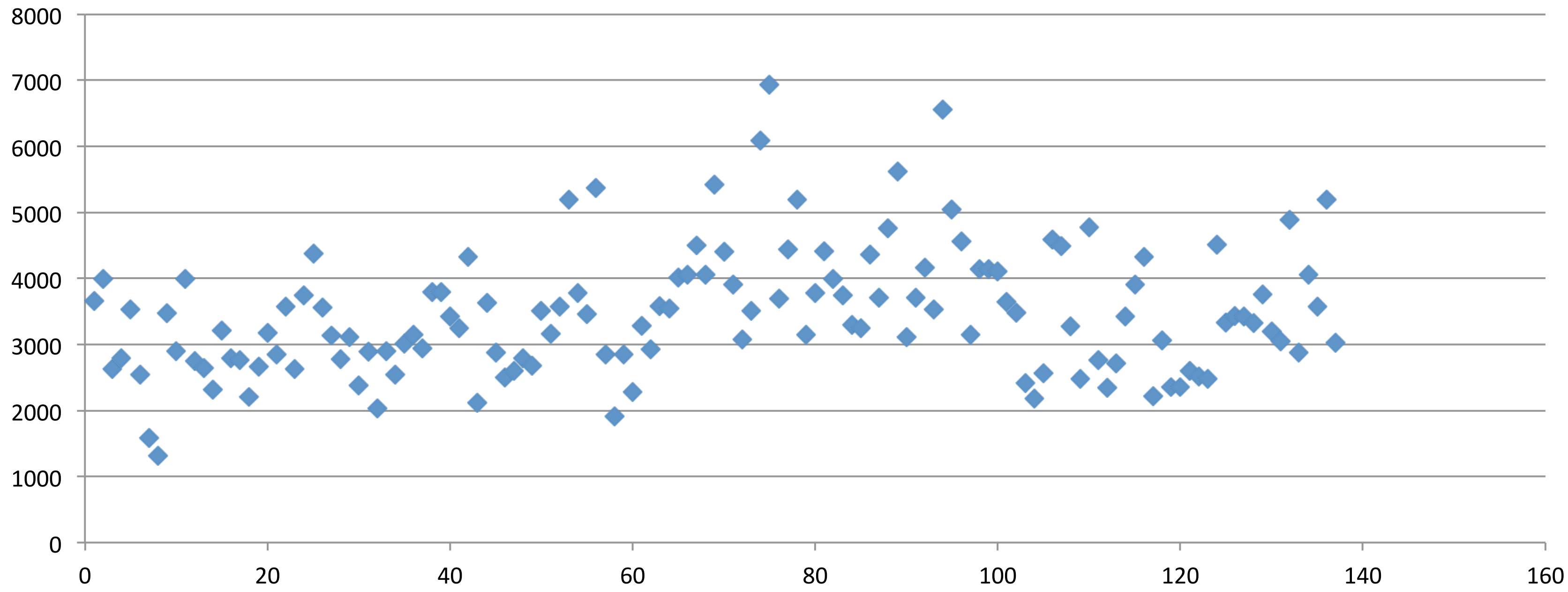
## Pre-Consultation Capital Cost Estimate

| | | | |
|---|---|---|---|
| NEA/IAE 2010 | (17 data) | Black & Veatch 2012 | (3 data) |
| Du & Parsons 2009 | (18 data) | USC 2010 & 2011 | (1 + 12 data) |
| U Chicago Update 2011 | (7 data) | Calif En Comm (CEC) 2010 | (1 data) |
| CEU COMM 2008 | (3 data) | BERR 2012 | (2 data) |
| Rothwell June 2010 | (5 data) | CBO 2008 | (1 data) |
| EPRI Update June 2011 | (2 data) | Harding 2008 | (4 data) |
| LUT 2012 | (2 data) | EIA AEO 2013 | (1 data) |
| Lazard 2008-11-12 | (2 data) | Keystone 2007 | (1 data) |
| IEA Stuttgart 2010 | (1 data) | Severance 2009 | (1 data) |
| ECN 2010 | (3 data) | Cooper 2009 (-10-11) | (14 data) |
| ICEPT 2012 | (15 data) | CRS (Kaplan) 2008 | (1 data) |
| Parsons Brinckerhoff 2011 | (6 data) | Lévêque 2013 | (2 data) |
| MMD 1010 and 2011 | (5 + 6 data) | VGB 2012 | (1 data) |

# Investment Cost of New NPPs

## Pre-Consultation Capital Cost Estimate

### Scatter plot of results (*EUR*$_{2012}$/*kW*$_{installed}$)

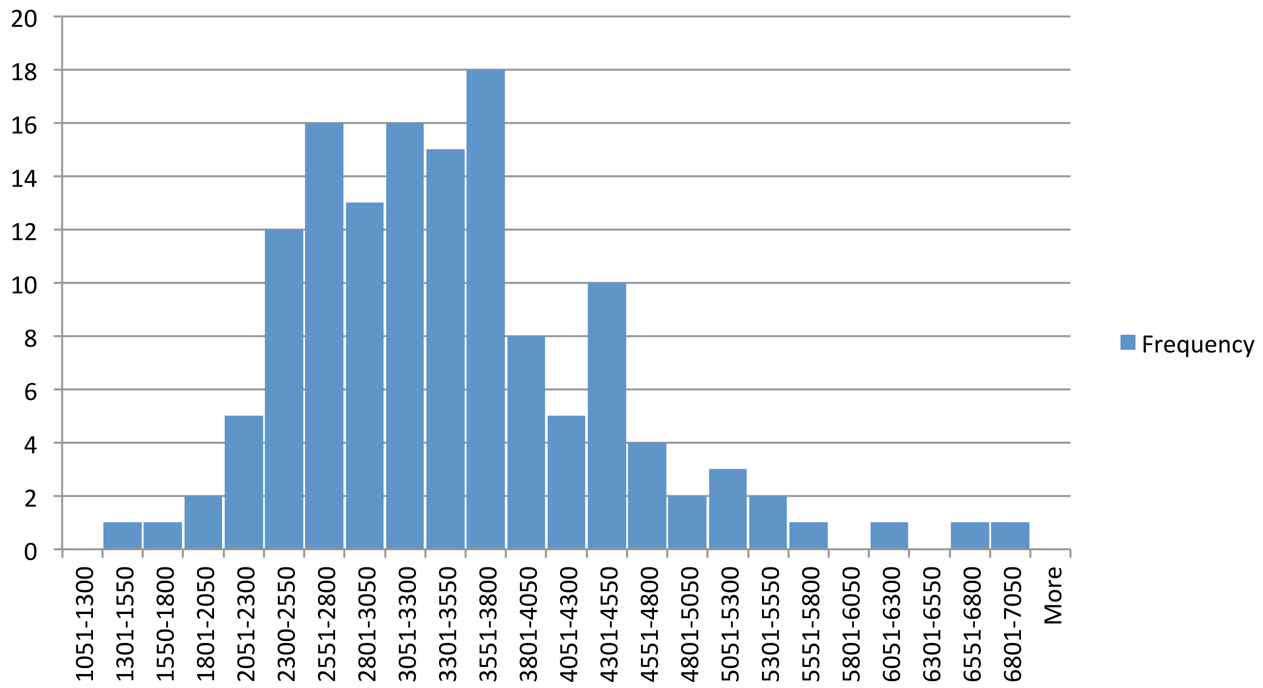



**Scatter plot for the 137 data points for the overnight construction cost (OCC) from a disparate set of references (mostly PWRs, but also a few BWRs, and so-called “generic” plants)**

# Investment Cost of New NPPs

## Pre-Consultation Capital Cost Estimate

### Histogram for the results (*$EUR_{2012}/kW_{installed}$*)

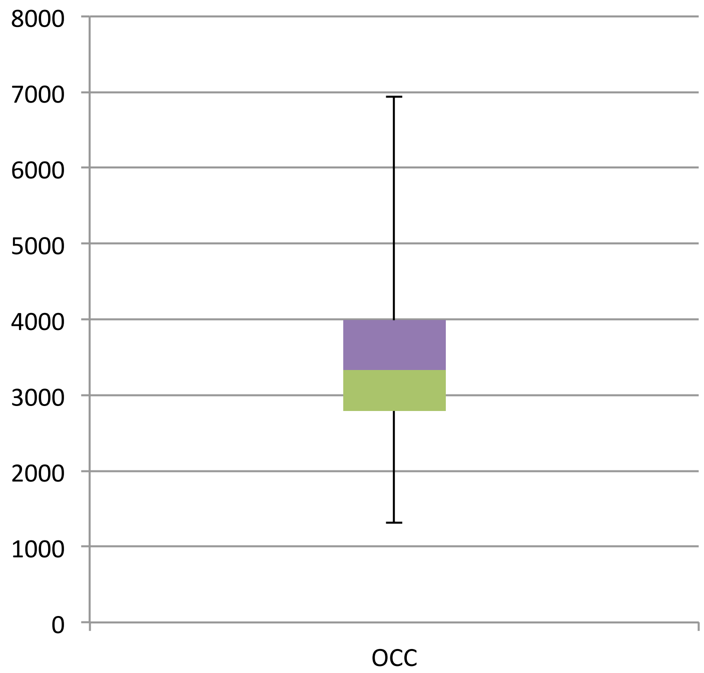



**Histogram for the 137 data points for the overnight construction cost (OCC) from a disparate set of references (mostly PWRs, but also a few BWRs, and so-called "generic" plants). The intervals of the bins are 250 $EUR_{2012}$ wide.**

# Investment Cost of New NPPs

## Pre-Consultation Capital Cost Estimate

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




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

## Chapter 3 Investment Cost of New NPPs

# 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**

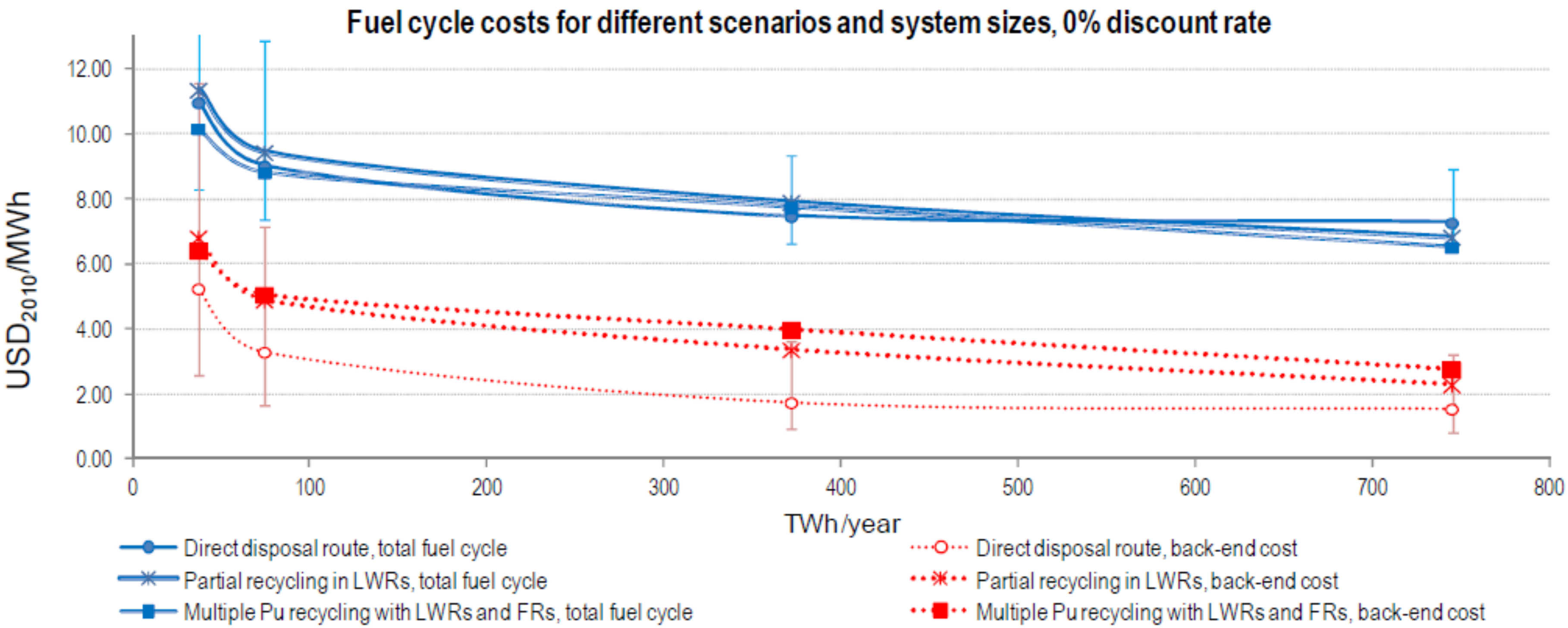
Note: Belgium ~50
Sweden ~60
UK ~ 70
FR ~ 400
USA ~ 800

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

# Fuel Cycle Costs and O&M Costs

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

- **Overall Results**



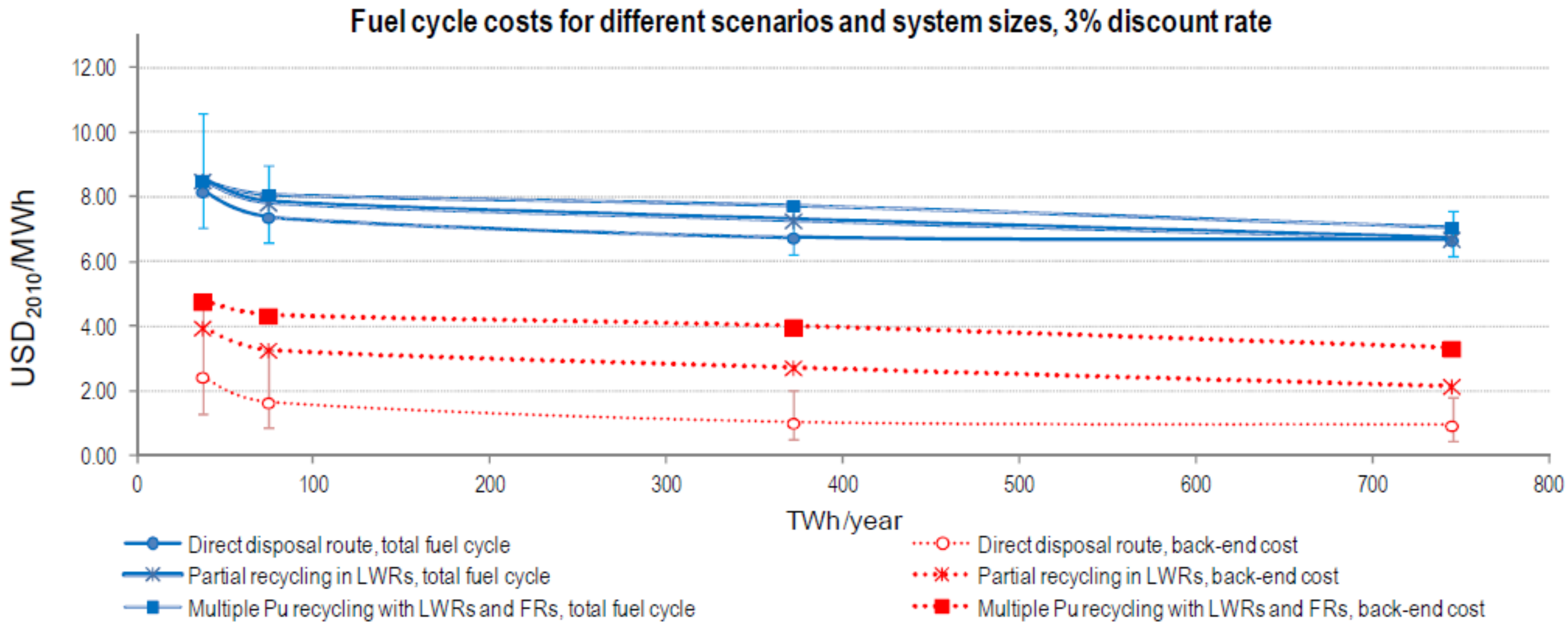

Note: Belgium ~50, Sweden ~60, UK ~ 70, FR ~ 400; USA ~ 800

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**



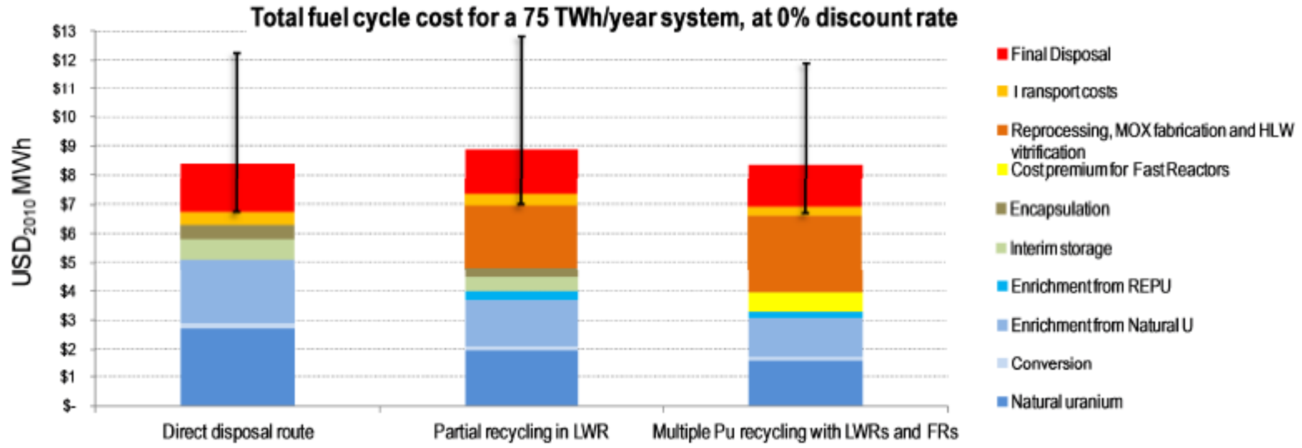

Note: The central values were calculated within the REFERENCE cost scenario, and the error bars correspond to LOW and HIGH cost scenarios.

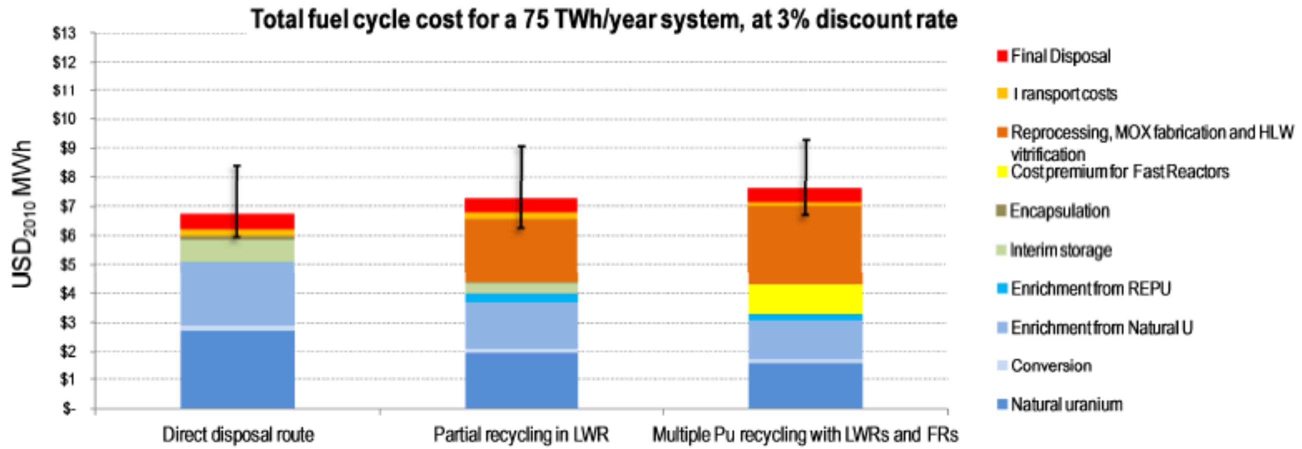
Note: Belgium ~50, Sweden ~60, UK ~ 70, FR ~ 400; USA ~ 800

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

# Fuel Cycle Costs and O&M Costs

**Figure 3.24 Fuel cycle cost decomposition for different scenarios, for a fleet generating 75 TWh/year, in REFERENCE cost level scenario, at 0% and3% discount rates**




Note: The calculations correspond to the REFERENCE cost scenario, and the error bars to LOW and HIGH cost scenarios.

# Fuel Cycle Costs and O&M Costs

- **Overall Results**

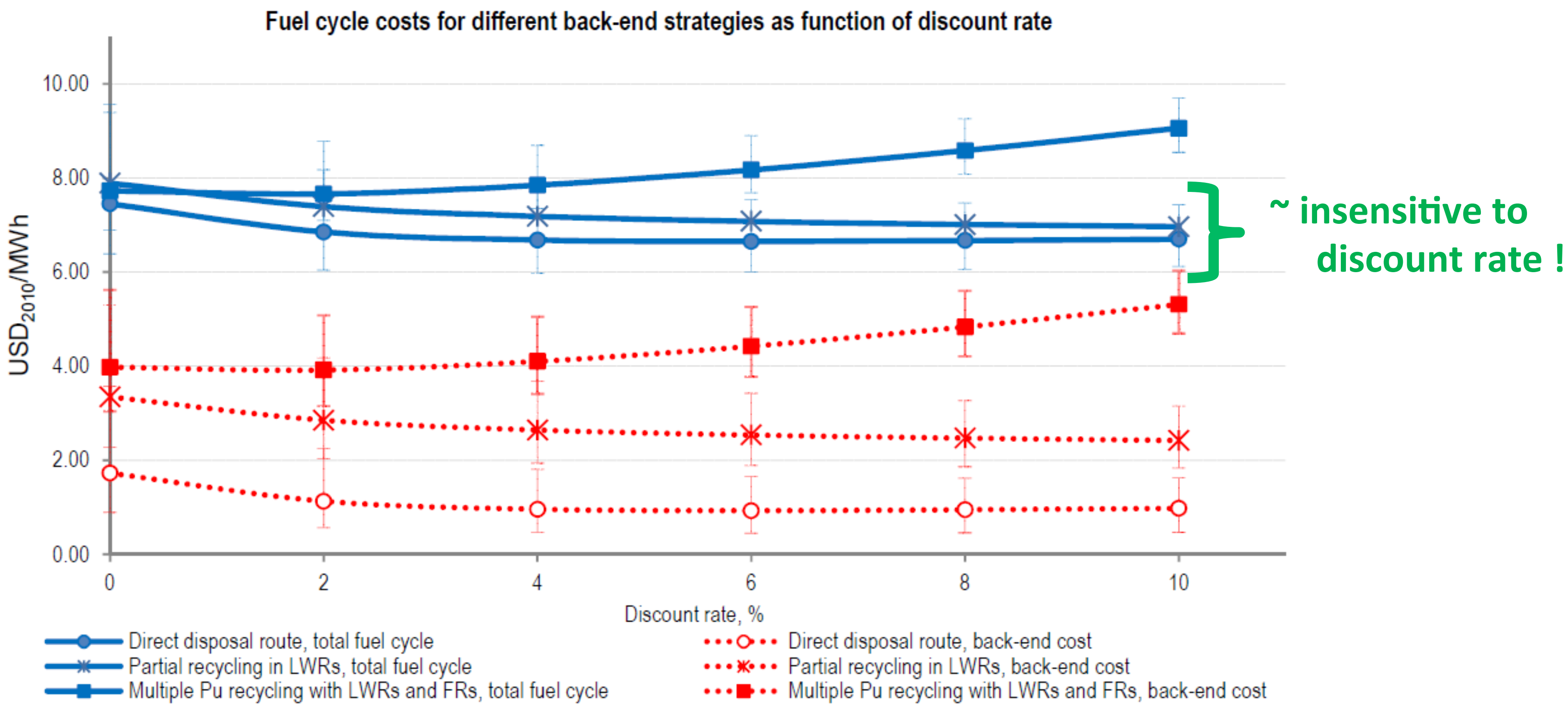
Bottomline conclusion:

- 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**, $USD_{2010}$/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**, $USD_{2010}$/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**, $USD_{2010}$/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)**

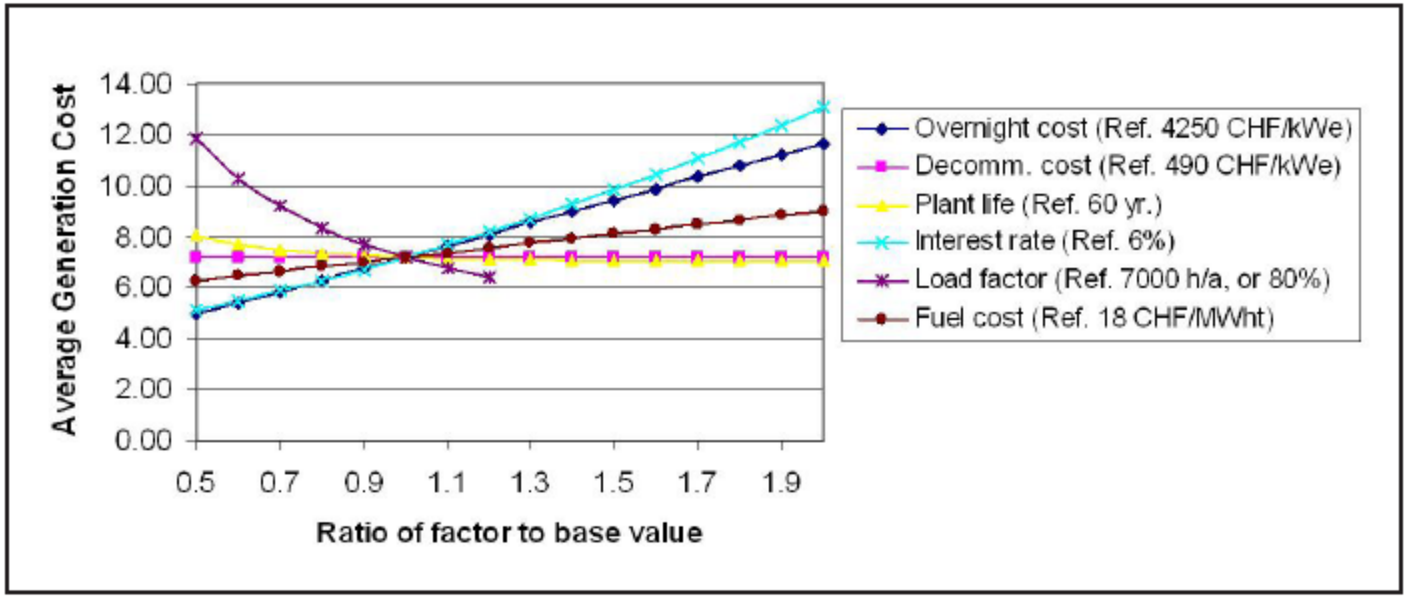



Figure 2: **Cost sensitivity for EPR.**

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

**Value of human life (VSL)**

- Viscusi (1998) "Rational Risk Policy" VSL ~ 3 -7 M$

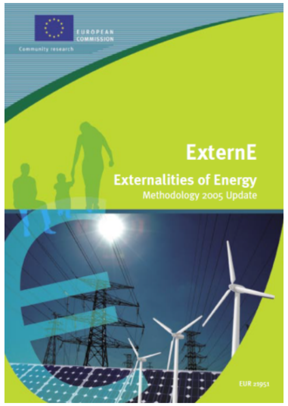
  OECD (2012) "Mortality Risk Valuation in Environment, Health and Transport Policies" VSL ~ 1.5 M€ - 4.5 M€

But also **VOLY (Value Of statistical Life Year)**

OECD (2012) ... For EU VOLY ~ 40,000 €/y

See also New ExternE methodology 2005:

§ 4.4 Monetary Valuation...



# External Costs / Externalities

**Recent values by Voss et al, 2013 (IER) – based on Externe, 2005**

**Value of human life (VSL)**

Voss (2013)... Value lost life ~ 1.3 M€

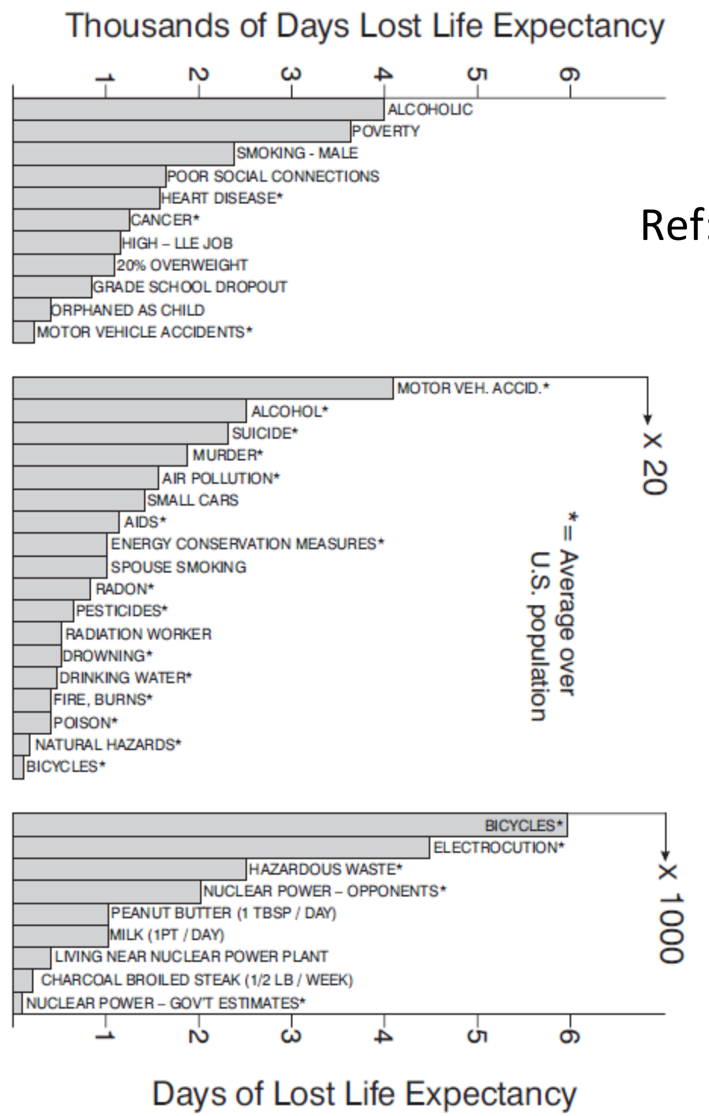
But also **VOLY (Value Of statistical Life Year)**

Voss (2013)... For EU VOLY ~ 60,000 €/y

# External Costs / Externalities

**Must take into account**
**Loss of Life Expectancy**
**in years...**

**Not all deaths are equivalent, young vs old**




Ref: B. L. Cohen

# External Costs / Externalities

**Discount factor** (up to 30-50 years, conventional social discount rate 3-8%; after that ~ 1-2%)

**Long-Term Discount Factors**

- Nice economic analysis by Lévêque (2013), going back to Ramsey (1928)
- Discusses "conflict" btwn N. Stern & W. Nordhaus on "The Economics of Climate Change"
- He "lands" with
  - Ch. Gollier (2002)
    - T < 30a, r=5% and T>31a, r = 2%
  - Oxera, UK (2002)
    - T < 30a, r=3.5% 75a>T>31a, r = 3%<br>125a>T>76a, r = 2.5% ... and T>300a, r=1%
  - Lebégue, FR (2005) – for all public investments
    - T < 30a, r=4% ...continuously... T=100a, r = 3%<br>...continuously... T=200a, r = 2%
- Other references: public policy appraisal ST ~ 3 - 4% LT ~ 0 - 1%

# 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

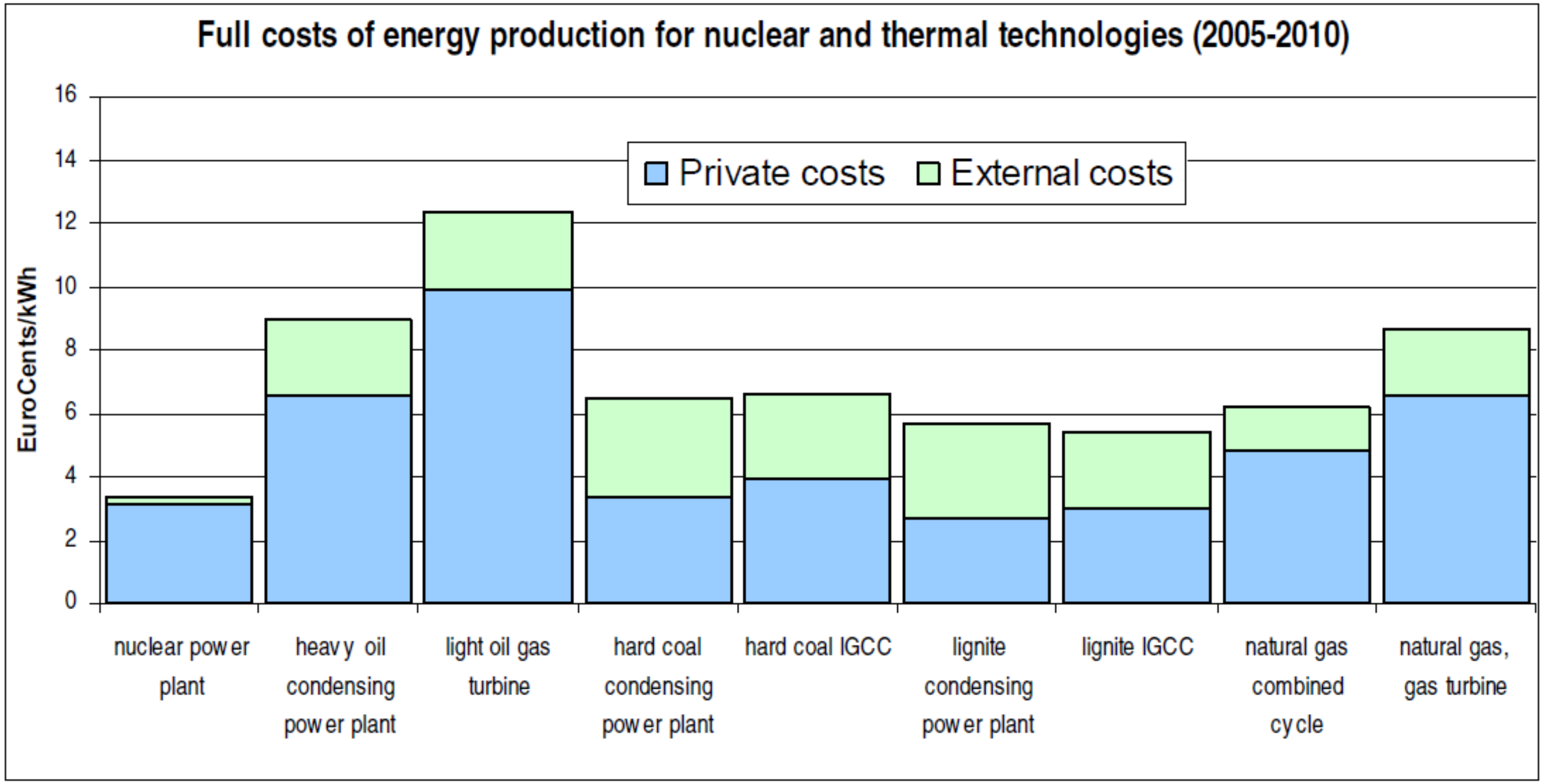
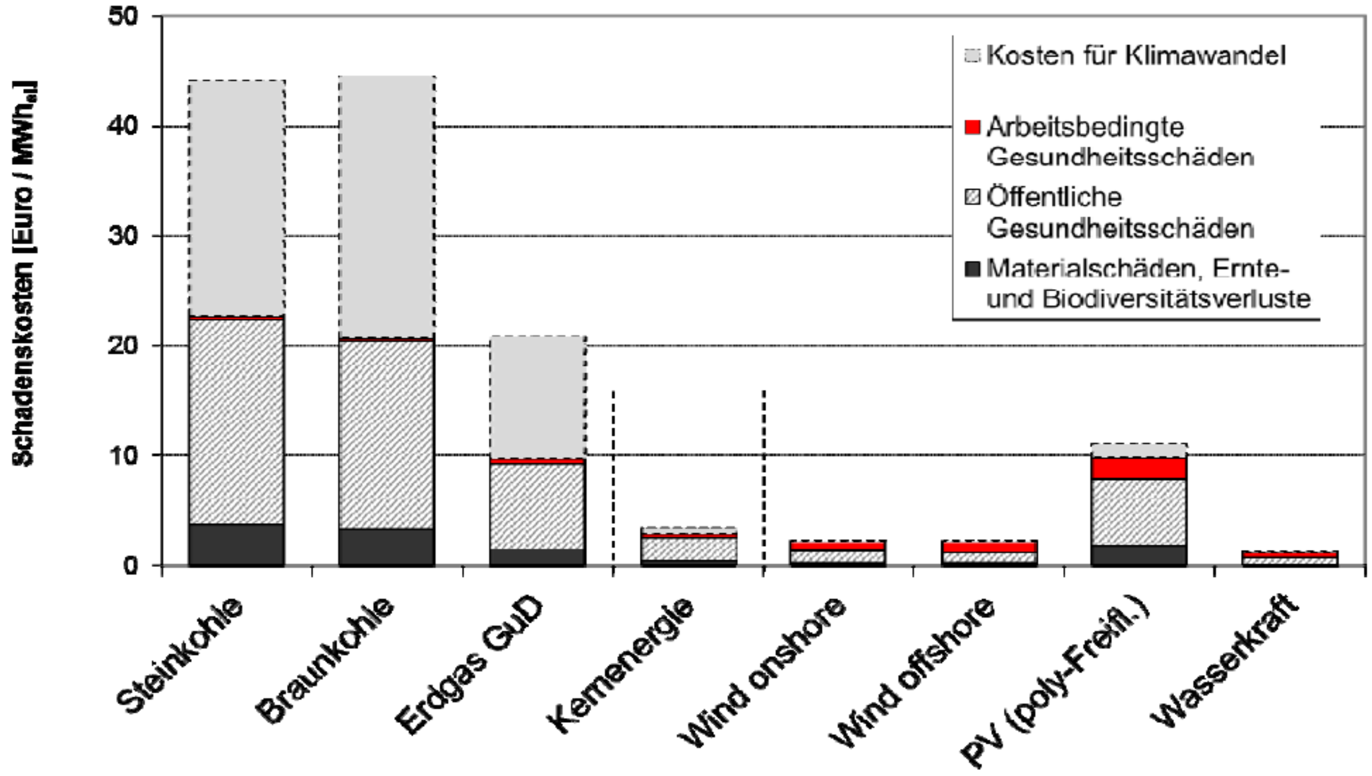



**Figure 4.1 Full cost composition for nuclear and fossil fired technologies in 2005-2010**

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

# External Costs / Externalities

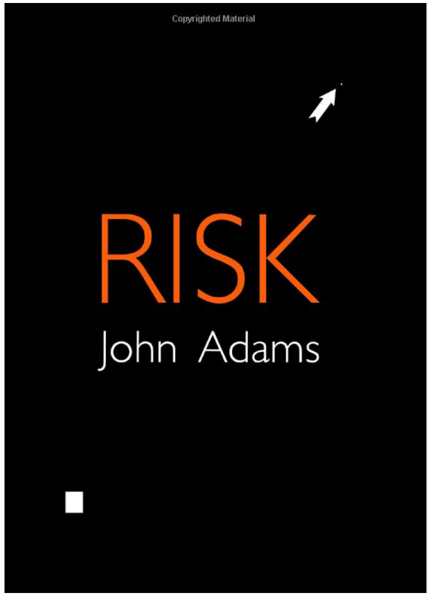


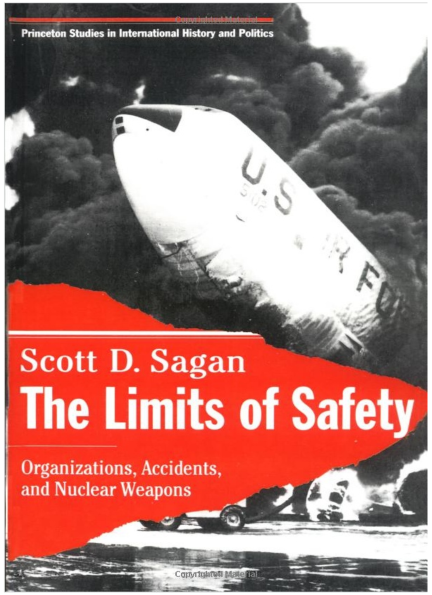

Ref: IER , Stuttgart (2013)

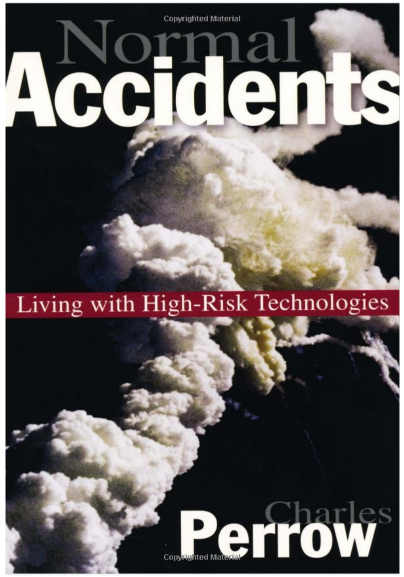
# Table of Contents

# Cost of Nuclear Accidents & Liability

Concept of "Risk" – sometimes controversial

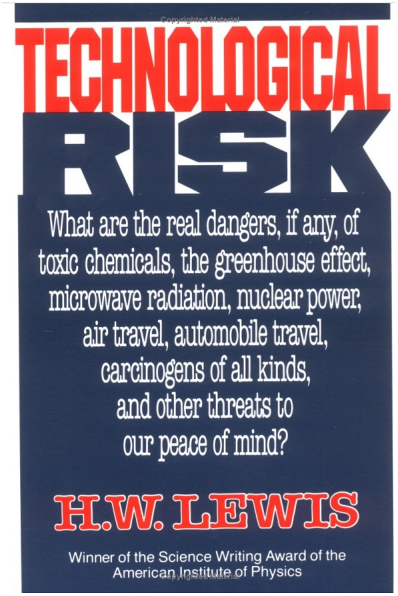


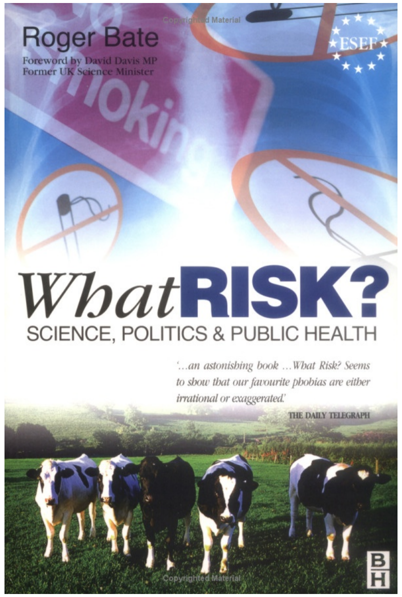



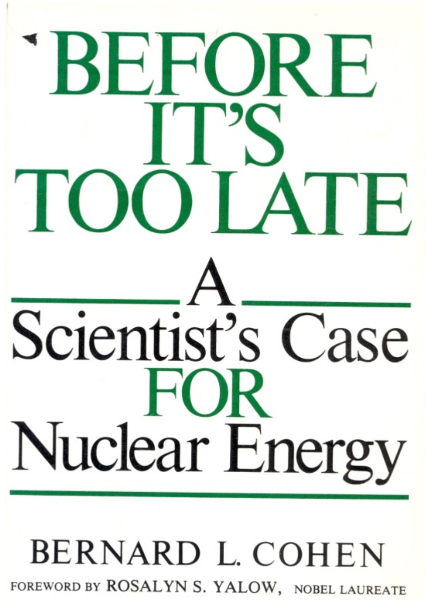



# Cost of Nuclear Accidents & Liability

Issue of Risk – sometimes controversial



# Cost of Nuclear Accidents & Liability

- Safety Technical Definition "Risk":

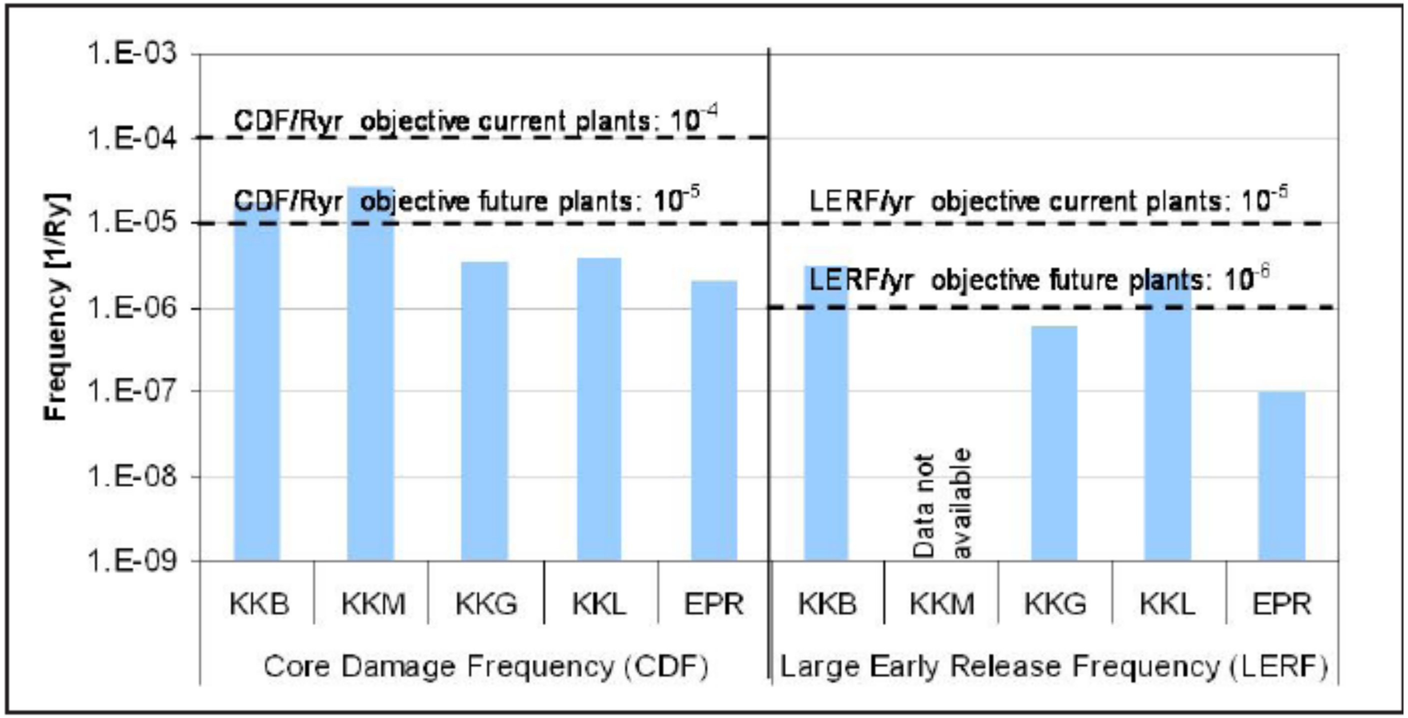
  **Risk = Probability x Effect**

- 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 x $10^{-4}$/react-a
     - for theoretical prob = 6.5 x $10^{-5}$/react-a
     - result Bayesian 'magic' → 3.2 x $10^{-4}$/react-a
     - but (WDH): this was for 11 'accidents' and CDF, not LERF
       → result is at least factor 10 smaller → 2 x $10^{-5}$/react-a

For damage of ~ 500 G€ and practical LERF= 2 x $10^{-5}$/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

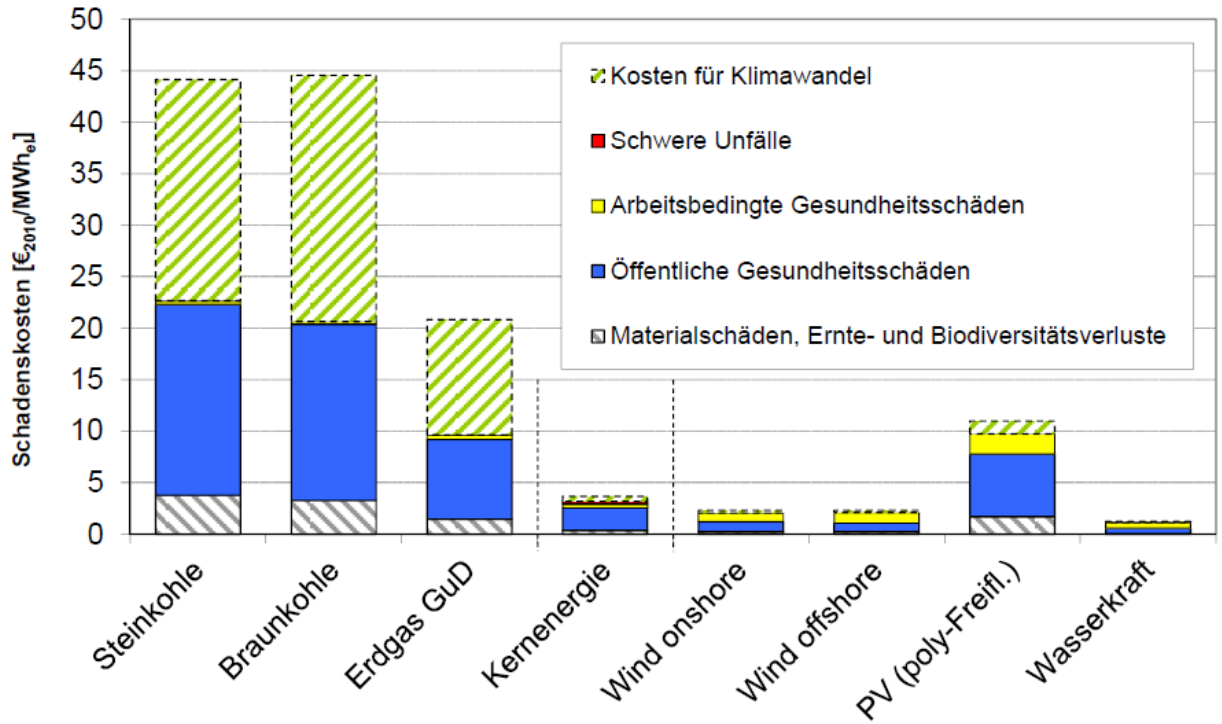



**Abbildung 6: Schadenskosten der Kernenergie im Vergleich mit anderen Stromerzeugungstechnologien**

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 can 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!**