Synthesis on the Economics of Nuclear Energy

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Synthesis on the Economics of Nuclear Energy

Study for the European Commission, DG Energy

Final Report

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Table of Contents

• Chapter 0  Objective / Terms of Study
• Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
• Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
• Chapter 3  Investment Cost of New NPPs
• Chapter 4  Investment Cost for Long-Term Operation (LTO)
• Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
• Chapter 6  Results LCOE of Nuclear Generation
• Chapter 7  External Costs / Externalities
• Chapter 8  Cost of Nuclear Accidents and Liability
• Chapter 9  System Costs
• Chapter 10 Overall Cost of Nuclear – Adding Things Together
• Chapter 11 Conclusions in Brief
# Table of Contents

- **Chapter 0**  Objective / Terms of Study
- **Chapter 1**  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- **Chapter 2**  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- **Chapter 3**  Investment Cost of New NPPs
- **Chapter 4**  Investment Cost for Long-Term Operation (LTO)
- **Chapter 5**  Fuel Cycle Costs and Operation & Maintenance (O&M)
- **Chapter 6**  Results LCOE of Nuclear Generation
- **Chapter 7**  External Costs / Externalities
- **Chapter 8**  Cost of Nuclear Accidents and Liability
- **Chapter 9**  System Costs
- **Chapter 10**  Overall Cost of Nuclear – Adding Things Together
- **Chapter 11**  Conclusions in Brief
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 varying 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 connoisseurs**!
# Table of Contents

- **Chapter 0**  Objective / Terms of Study  
- **Chapter 1**  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity  
- **Chapter 2**  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues  
- **Chapter 3**  Investment Cost of New NPPs  
- **Chapter 4**  Investment Cost for Long-Term Operation (LTO)  
- **Chapter 5**  Fuel Cycle Costs and Operation & Maintenance (O&M)  
- **Chapter 6**  Results LCOE of Nuclear Generation  
- **Chapter 7**  External Costs / Externalities  
- **Chapter 8**  Cost of Nuclear Accidents and Liability  
- **Chapter 9**  System Costs  
- **Chapter 10**  Overall Cost of Nuclear – Adding Things Together  
- **Chapter 11**  Conclusions in Brief
Table of Contents

Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity

1.1 Concept of Cost
1.2 Cost Elements Nuclear Generation
1.3 Type of Investor
1.4 Levelized Cost of Electricity (LCOE)

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

- Investment: 60%
- O&M: 25%
- Fuel cycle: 15%*

* The cost of natural uranium typically represents only 5%.
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 the fuel cycle; often already internalized)
  - Accidents – liability
  - Proliferation
  - Avoided CO\textsubscript{2} emissions – a positive externality? (Also the small amount of embedded CO\textsubscript{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

Case 1: 10% discount rate, 2011 project start, FOAK/NOAK mix

Case 2: 10% discount rate, 2017 project start, all NOAK
LCOE - Illustrations

Case 1: Project Start 2013, FOAK/NOAK, 10% discount rate

UK Figures
Parsons & Brinckerhoff 2013
GBP_{2012}/MWh

Case 2: Project Start 2019, FOAK/NOAK, 10% discount rate
Table of Contents

- Chapter 0  Objective / Terms of Study
- Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- Chapter 3  Investment Cost of New NPPs
- Chapter 4  Investment Cost for Long-Term Operation (LTO)
- Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
- Chapter 6  Results LCOE of Nuclear Generation
- Chapter 7  External Costs / Externalities
- Chapter 8  Cost of Nuclear Accidents and Liability
- Chapter 9  System Costs
- Chapter 10  Overall Cost of Nuclear – Adding Things Together
- Chapter 11  Conclusions in Brief
Table of Contents

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

2.1  PWR –BWR Generic Estimate
2.2  Fuel Cycle: Upstream /Downstream - Decommissioning
2.3  Investment Cost – Definition
2.4  LCOE – Computational Guidelines
2.5  Exchange Rates
2.6  Inflation – Escalation
2.7  Costs of “final proposal” expressed in EUR 2012
2.8  Discount rates / WACC: definition
2.9  Discount rates used in study: 5% and 10% in real terms
2.10  No taxes or subsidies considered
2.11  Lifetime 60 years
2.12  First fuel load not considered in investment cost (~ 3% of OCC)
2.13  Lifetime Availability factor 85%
2.14  Uncertainties and Accuracy of Estimate

Crucial Chapter!
Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues

2.1  PWR – BWR Generic Estimate
2.2  Fuel Cycle: Upstream / Downstream - Decommissioning
2.3  Investment Cost – Definition
2.4  LCOE – Computational Guidelines
2.5  Exchange Rates
2.6  Inflation – Escalation
2.7  Costs of “final proposal” expressed in EUR 2012
2.8  Discount rates / WACC: definition
2.9  Discount rates used in study: 5% and 10% in real terms
2.10  No taxes or subsidies considered
2.11  Lifetime 60 years
2.12  First fuel load not considered in investment cost (~ 3% of OCC)
2.13  Lifetime Availability factor 85%
2.14  Uncertainties and Accuracy of Estimate
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

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

2.1  PWR –BWR Generic Estimate
2.2  Fuel Cycle: Upstream /Downstream - Decommissioning
2.3  Investment Cost – Definition
2.4  LCOE – Computational Guidelines
2.5  Exchange Rates
2.6  Inflation – Escalation
2.7  Costs of “final proposal” expressed in EUR 2012
2.8  Discount rates / WACC: definition
2.9  Discount rates used in study: 5% and 10% in real terms
2.10  No taxes or subsidies considered
2.11  Lifetime 60 years
2.12  First fuel load not considered in investment cost (~ 3% of OCC)
2.13  Lifetime Availability factor 85%
2.14  Uncertainties and Accuracy of Estimate
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
Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues

2.1 PWR –BWR Generic Estimate
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
2.7 Costs of “final proposal” expressed in EUR 2012
2.8 Discount rates / WACC: definition
2.9 Discount rates used in study: 5% and 10% in real terms
2.10 No taxes or subsidies considered
2.11 Lifetime 60 years
2.12 First fuel load not considered in investment cost (~ 3% of OCC)
2.13 Lifetime Availability factor 85%
2.14 Uncertainties and Accuracy of Estimate
Definitions, Conventions ...

Investment Cost – Definition
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]
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

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

2.1  PWR –BWR Generic Estimate
2.2  Fuel Cycle: Upstream /Downstream - Decommissioning
2.3  Investment Cost – Definition
2.4  LCOE – Computational Guidelines
2.5  Exchange Rates
2.6  Inflation – Escalation
2.7  Costs of “final proposal” expressed in EUR 2012
2.8  Discount rates / WACC: definition
2.9  Discount rates used in study: 5% and 10% in real terms
2.10  No taxes or subsidies considered
2.11  Lifetime 60 years
2.12  First fuel load not considered in investment cost (~ 3% of OCC)
2.13  Lifetime Availability factor 85%
2.14  Uncertainties and Accuracy of Estimate
Definitions, Conventions ...

LCOE – Computational Guidelines

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

Example for new build:

$$\Sigma_t (Electricity_t \cdot P_{Electricity} \cdot (1+r)^{-t}) =$$

$$\Sigma_t ((Investment_t + O&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t})$$

(1).

From (1) follows that

$$P_{Electricity} =$$

$$\Sigma_t ((Investment_t + O&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t (Electricity_t *(1+r)^{-t}))$$

(2),

which is, of course, equivalent to

$$LCOE = P_{Electricity} =$$

$$\Sigma_t ((Investment_t + O&M_t + Fuel_t + Carbon_t + Decommissioning_t)*(1+r)^{-t}) / (\Sigma_t (Electricity_t *(1+r)^{-t}))$$

(2)’.
Chapter 2 Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues

2.1 PWR –BWR Generic Estimate
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
2.7 Costs of “final proposal” expressed in EUR 2012
2.8 Discount rates / WACC: definition
2.9 Discount rates used in study: 5% and 10% in real terms
2.10 No taxes or subsidies considered
2.11 Lifetime 60 years
2.12 First fuel load not considered in investment cost (~ 3% of OCC)
2.13 Lifetime Availability factor 85%
2.14 Uncertainties and Accuracy of Estimate
Definitions, Conventions ...

**Exchange Rates**

*Use Market Exchange Rates (MER):*

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

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

2.1 PWR –BWR Generic Estimate  
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning  
2.3 Investment Cost – Definition  
2.4 LCOE – Computational Guidelines  
2.5 Exchange Rates  
2.6 Inflation – Escalation  
2.7 Costs of “final proposal” expressed in EUR 2012  
2.8 Discount rates / WACC: definition  
2.9 Discount rates used in study: 5% and 10% in real terms  
2.10 No taxes or subsidies considered  
2.11 Lifetime 60 years  
2.12 First fuel load not considered in investment cost (~ 3% of OCC)  
2.13 Lifetime Availability factor 85%  
2.14 Uncertainties and Accuracy of Estimate
Table of Contents

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

2.1  PWR – BWR Generic Estimate
2.2  Fuel Cycle: Upstream / Downstream - Decommissioning
2.3  Investment Cost – Definition
2.4  LCOE – Computational Guidelines
2.5  Exchange Rates
2.6  Inflation – Escalation
   2.6.1 Inflation and Escalation
   2.6.2 Historic Escalation of the Cost of NPPs
      2.6.2.1 In the USA
      2.6.2.2 The French Case (Grubler versus Lévêque)
2.6.3 Learning Effects / Fleet Effect
2.6.4 Pragmatic Approach on Cost Escalation – Own Analysis
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 $\text{Esc}_2$

IHS CERA Power Capital Cost Indices ($\text{Esc}_2$) compared to usual inflation ($\text{Esc}_1$)
# Table of Contents

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

2.1 PWR –BWR Generic Estimate  
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning  
2.3 Investment Cost – Definition  
2.4 LCOE – Computational Guidelines  
2.5 Exchange Rates  
2.6 Inflation – Escalation  
  2.6.1 Inflation and Escalation  
  2.6.2 Historic Escalation of the Cost of NPPs  
    2.6.2.1 In the USA  
    2.6.2.2 The French Case (Grubler versus Lévêque)  
2.6.3 Learning Effects / Fleet Effect  
2.6.4 Pragmatic Approach on Cost Escalation – Own Analysis
Definitions, Conventions ...

Inflation – Escalation

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

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 *real construction* 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 real construction costs of NPPs – FR
Lévêque, considers the different ‘paliers’ and ‘types’
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 \(\rightarrow\) 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

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

2.1 PWR –BWR Generic Estimate
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
  2.6.1 Inflation and Escalation
  2.6.2 Historic Escalation of the Cost of NPPs
      2.6.2.1 In the USA
      2.6.2.2 The French Case (Grubler versus Lévêque)
  2.6.3 Learning Effects / Fleet Effect
  2.6.4 Pragmatic Approach on Cost Escalation – Own Analysis
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 →
Definitions, Conventions ...

Inflation – Escalation

Learning Effects / Fleet Effect

Inflation – Escalation

Learning Effects / Fleet Effect

Define two types of **FOAK** (First of a Kind):

- **FOAK** sub 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** sub 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** sub 2 (5+) or **NOAK** sub 2 (6+)

- Also, to distinguish between **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

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**

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

2.1 PWR –BWR Generic Estimate
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
   2.6.1 Inflation and Escalation
   2.6.2 Historic Escalation of the Cost of NPPs
      2.6.2.1 In the USA
      2.6.2.2 The French Case (Grubler versus Lévêque)
   2.6.3 Learning Effects / Fleet Effect
   2.6.4 Pragmatic Approach on Cost Escalation – Own Analysis
Definitions, Conventions ...

Inflation – Escalation

Pragmatic Approach on Cost Escalation – Own Analysis

Red curves are PCCIs for nuclear only – estimates
Green curves are simplifying fits / ignoring overshoot
Definitions, Conventions ...

Inflation – Escalation

<table>
<thead>
<tr>
<th>North America</th>
<th>Annual percentage growth</th>
<th>EUR</th>
<th>Annual percentage growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000-2005</td>
<td>~ 5%/a</td>
<td></td>
<td>2000-2005</td>
</tr>
<tr>
<td>2007-2013</td>
<td>~ 2%/a</td>
<td></td>
<td>2007-2013</td>
</tr>
</tbody>
</table>

Future escalation? Perhaps normal inflation and 5%/a; But we’ll consider margin of uncertainties
# Table of Contents

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

2.1 PWR –BWR Generic Estimate  
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning  
2.3 Investment Cost – Definition  
2.4 LCOE – Computational Guidelines  
2.5 Exchange Rates  
2.6 Inflation – Escalation  
2.7 Costs of “final proposal” expressed in EUR 2012  
2.8 Discount rates / WACC: definition  
2.9 Discount rates used in study: 5% and 10% in real terms  
2.10 No taxes or subsidies considered  
2.11 Lifetime 60 years  
2.12 First fuel load *not* considered in investment cost (~ 3% of OCC)  
2.13 Lifetime Availability factor 85%  
2.14 Uncertainties and Accuracy of Estimate
Definitions, Conventions ...

Discount Rates / WACC definition

\[ WACC = r_{\text{deb}} \left( \frac{D}{V} \right) \left( 1 - t_c \right) + r_{\text{equity}} \left( \frac{E}{V} \right) \]

with

- \( r_{\text{deb}} \) = interest rate on debt
- \( r_{\text{equity}} \) = 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

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

- Real (gross) discount rate

\[
(r_{eff})^{real} = \frac{1 + (r_{eff})^{nom}}{1 + i} - 1
\]

with

\[i = \text{inflation rate.}\]

MIT, 2003 and 2009

\[
(r_{eff})^{nom} = 11.3\%; \quad \text{WACC} = 10\%
\]

\[
r_{debt} = 8\% \quad r_{equity} = 15\%\]

50/50 debt/equity; corp tax 38%

MIT, 2003 and 2009

\[i = 3\%/a \Rightarrow (r_{eff})^{real} = 11.3\%\]

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

For public investors, \((r_{eff})^{nom} \sim 3\text{-}4\%/a\) (all debt; through –government – bonds)
Discount Rates / WACC definition

Discount rates used in this study:

5%/a and 10%/a in real terms
Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues

2.1 PWR – BWR Generic Estimate
2.2 Fuel Cycle: Upstream / Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
2.7 Costs of “final proposal” expressed in EUR 2012
2.8 Discount rates / WACC: definition
2.9 Discount rates used in study: 5% and 10% in real terms
2.10 No taxes or subsidies considered
2.11 Lifetime 60 years
2.12 First fuel load not considered in investment cost (~ 3% of OCC)
2.13 Lifetime Availability factor 85%
2.14 Uncertainties and Accuracy of Estimate
Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues

2.1 PWR –BWR Generic Estimate
2.2 Fuel Cycle: Upstream /Downstream - Decommissioning
2.3 Investment Cost – Definition
2.4 LCOE – Computational Guidelines
2.5 Exchange Rates
2.6 Inflation – Escalation
2.7 Costs of “final proposal” expressed in EUR 2012
2.8 Discount rates / WACC: definition
2.9 Discount rates used in study: 5% and 10% in real terms
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2.11 Lifetime 60 years
2.12 First fuel load not considered in investment cost (~ 3% of OCC)
2.13 Lifetime Availability factor 85%
2.14 Uncertainties and Accuracy of Estimate
### Uncertainties and Accuracy of Estimate

#### Level of Accuracy of the cost estimate:

<table>
<thead>
<tr>
<th>ESTIMATE CLASS</th>
<th>LEVEL OF PROJECT DEFINITION</th>
<th>END USAGE</th>
<th>METHODOLOGY</th>
<th>EXPECTED ACCURACY RANGE</th>
<th>PREPARATION EFFORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 5</td>
<td>0% to 2%</td>
<td>Concept Screening</td>
<td>Capacity Factored, Parametric Models, Judgment, or Analogy</td>
<td>L: -20% to -50% H: +30% to +100%</td>
<td>1</td>
</tr>
<tr>
<td>Class 4</td>
<td>1% to 15%</td>
<td>Study or Feasibility</td>
<td>Equipment Factored or Parametric Models</td>
<td>L: -15% to -30% H: +20% to +50%</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Class 3</td>
<td>10% to 40%</td>
<td>Budget, Authorization, or Control</td>
<td>Semi-Detailed Unit Costs with Assembly Level Line Items</td>
<td>L: -10% to -20% H: +10% to +30%</td>
<td>3 to 10</td>
</tr>
<tr>
<td>Class 2</td>
<td>30% to 70%</td>
<td>Control or Bid/Tender</td>
<td>Detailed Unit Cost with Forced Detailed Take-Off</td>
<td>L: -5% to -15% H: +5% to +20%</td>
<td>4 to 20</td>
</tr>
<tr>
<td>Class 1</td>
<td>50% to 100%</td>
<td>Check Estimate or Bid/Tender</td>
<td>Detailed Unit Cost with Detailed Take-Off</td>
<td>L: -3% to -10% H: +3% to +15%</td>
<td>5 to 100</td>
</tr>
</tbody>
</table>

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.

Association for the Advancement of Cost Engineering International; Recommended Practice 18R-97
Uncertainties and Accuracy of Estimate

Level of Accuracy of the cost estimate:

Our estimates:

**FOAK$_2$**; generic estimate btwn classes 3 and 5
\[ \rightarrow \text{accuracy btwn -20\% to +30\%} \]

**NOAK$_2$(5+)** btwn classes 1 and 3
\[ \rightarrow \text{accuracy btwn -10\% to +15\%} \]
Definitions, Conventions ... 

Uncertainties and Accuracy of Estimate

Contingency:

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

• FOAK₁ contingency 30-50% (but not relevant to our report);
• FOAK₂ 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);
• NOAK₂(10+) 10-15% seems reasonable

We take a *generic* contingency of 15% for NOAK₂(5+) and set penalties for FOAK₂
Definitions, Conventions ...

Uncertainties and Accuracy of Estimate

Proposed Overnight Capital Cost (OCC) levels:

- AVERAGE ≡ AVE (incl 15% contingency)
- AVE + 50% FOAK₁ (generic)
- AVE + 20% FOAK₂ (generic)
- AVE + 5% NOAK₁ (gen)
- AVE - 15% NOAK₂ (10+) (gen)
- AVE - 10% NOAK₂ / single
- AVE - 20% NOAK₂ / twin
- AVE + 55% FOAK₁ / single
- AVE + 45% FOAK₁ / twin
- AVE + 25% FOAK₂ / single
- AVE + 15% FOAK₂ / twin
- AVE + 5% NOAK₂ / single
- AVE - 5% NOAK₂ / twin
- Greenfield AVE + 65%
- Brownfield AVE + 55%
- ..../..
- Greenfield AVE + 35%
- ..../..
- Brownfield AVE + 15%
- Greenfield AVE + 15%
- ..../..
- Greenfield AVE + 10%

Δ (single - twin) = 10% pts
Penalty greenfield = 10% pts
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

- **Chapter 0** Objective / Terms of Study
- **Chapter 1** Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- **Chapter 2** Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- **Chapter 3** Investment Cost of New NPPs
- **Chapter 4** Investment Cost for Long-Term Operation (LTO)
- **Chapter 5** Fuel Cycle Costs and Operation & Maintenance (O&M)
- **Chapter 6** Results LCOE of Nuclear Generation
- **Chapter 7** External Costs / Externalities
- **Chapter 8** Cost of Nuclear Accidents and Liability
- **Chapter 9** System Costs
- **Chapter 10** Overall Cost of Nuclear – Adding Things Together
- **Chapter 11** Conclusions in Brief
Table of Contents

Chapter 3  Investment Cost of New NPPs

3.1  Variation of Estimates – Illustrations
3.2  Capital Cost Estimate of this Study

First attempt to converge on Overnight Capital Construction Cost
Table of Contents

Chapter 3  Investment Cost of New NPPs

3.1  Variation of Estimates – Illustrations
3.2  Capital Cost Estimate of this Study
Investment Cost of New NPPs

Variation of estimates – Illustrations – geographical

![Chart: Overnight Costs of Electricity Generating Technologies ($/kw)](chart.png)


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)*

<table>
<thead>
<tr>
<th>Year of construction start</th>
<th>Number of plants</th>
<th>Initial estimate</th>
<th>Realised costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966-1967</td>
<td>11</td>
<td>530</td>
<td>1109</td>
</tr>
<tr>
<td>1968-1969</td>
<td>26</td>
<td>643</td>
<td>1062</td>
</tr>
<tr>
<td>1970-1971</td>
<td>12</td>
<td>719</td>
<td>1407</td>
</tr>
<tr>
<td>1972-1973</td>
<td>7</td>
<td>1057</td>
<td>1891</td>
</tr>
<tr>
<td>1974-1975</td>
<td>14</td>
<td>1095</td>
<td>2346</td>
</tr>
<tr>
<td>1976-1977</td>
<td>5</td>
<td>1413</td>
<td>2132</td>
</tr>
</tbody>
</table>

Note: Original data expressed in $1982.
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.
Investment Cost of New NPPs

Variation of estimates – Illustrations
– variation in time of ‘recent’ estimates

UChicago 2011
Chapter 3  Investment Cost of New NPPs

3.1  Variation of Estimates – Illustrations
  3.1.1 Geographic Variation
  3.1.2 Discrepancy Cost Estimations and Actual Construction Costs
  3.1.3 Variation in Time of “Recent” Cost Estimates

3.2  Capital Cost Estimate of This Study
  2.3.1 Pre-Consultation Estimate
  2.3.2 Consultation of Academics and Nuclear Market Actors
  2.3.3 Overnight Cost New Build – Post-Consultation Wrap Up
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 ($EUR_{2012}/kW_{\text{installed}}$)

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 \( (EUR_{2012}/kW_{\text{installed}}) \)

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 \((EUR_{2012}/kW_{\text{installed}})\)

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

$\text{FOAK}_2$: 

= about $3910 \text{EUR}_{2012}/\text{kW}$ for $\text{FOAK}_2$ with uncertainty -20% to +30% on a brownfield, for a twin unit

= about $4250 \text{EUR}_{2012}/\text{kW}$ for $\text{FOAK}_2$ with uncertainty -20% to +30% on a brownfield, for a single unit
Chapter 3  Investment Cost of New NPPs

3.1 Variation of Estimates – Illustrations
   3.1.1 Geographic Variation
   3.1.2 Discrepancy Cost Estimations and Actual Construction Costs
   3.1.3 Variation in Time of “Recent” Cost Estimates

3.2 Capital Cost Estimate of This Study
   2.3.1 Pre-Consultation Estimate
   2.3.2 Consultation of Academics and Nuclear Market Actors
   2.3.3 Overnight Cost New Build – Post-Consultation Wrap Up
Synthesis on the economics of nuclear energy
Study for the European Commission, DG Energy
Service Contract N° ENER/2012/NUCL/S/2.643067

Draft Intermediate Report

May 20, 2013

William D. D’haeseleer

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

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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
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 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 €\textsubscript{2012}/kW
  - Applicable for NOAK\textsubscript{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 in projects 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 €/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 FOAK₁ single unit on Brownfield»
  – Actually EPR Flam is a FOAK₂ 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**

3.1 Variation of Estimates – Illustrations
   3.1.1 Geographic Variation
   3.1.2 Discrepancy Cost Estimations and Actual Construction Costs
   3.1.3 Variation in Time of “Recent” Cost Estimates

3.2 Capital Cost Estimate of This Study
   2.3.1 Pre-Consultation Estimate
   2.3.2 Consultation of Academics and Nuclear Market Actors
   2.3.3 Overnight Cost New Build – Post-Consultation Wrap Up
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 €\textsubscript{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 €\textsubscript{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,

\[
\text{OCC : 2,900...3,540...4,200 €/kW} \]


‘12 \( \rightarrow 4,217 \text{ €}_{2012}/\text{kW} \) for NOAK (3 units), and \( 4,960 \text{ €}_{2012}/\text{kW} \) for FOAK\(_2\) (3 units)

‘13 \( \rightarrow 4,762 \text{ €}_{2012}/\text{kW} \) for NOAK (3 units), and \( 5,452 \text{ €}_{2012}/\text{kW} \) for FOAK\(_2\) (3 units)

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

- For NOAK₂ (5+) on a brownfield: 3,060...3,400...3,910 €₂₀₁₂/kW
- For FOAK₂ twin unit on brownfield: 3,128...3,910...5,083 €₂₀₁₂/kW
- For FOAK₂ single unit on brownfield: 3,400...4,250...5,525 €₂₀₁₂/kW
# Table of Contents

- **Chapter 0**  
  Objective / Terms of Study
- **Chapter 1**  
  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- **Chapter 2**  
  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- **Chapter 3**  
  Investment Cost of New NPPs
- **Chapter 4**  
  Investment Cost for Long-Term Operation (LTO)
- **Chapter 5**  
  Fuel Cycle Costs and Operation & Maintenance (O&M)
- **Chapter 6**  
  Results LCOE of Nuclear Generation
- **Chapter 7**  
  External Costs / Externalities
- **Chapter 8**  
  Cost of Nuclear Accidents and Liability
- **Chapter 9**  
  System Costs
- **Chapter 10**  
  Overall Cost of Nuclear – Adding Things Together
- **Chapter 11**  
  Conclusions in Brief
Investment for LTO / Refurbishments

- Range of Overnight Refurbishment Cost \( \sim 500 - 1,100 \ $/kW \)

  or with \( 1 \ $_{2010} = 0.754 \ €_{2010} \) \( \rightarrow \) range \( \sim 377 - 830 \ €/kW, \)

  or thus \( \sim 400 - 850 \ €_{2012}/kW \) for additional lifetime of

  up to \( \sim 20 \) years

Note: \( €_{2010} = 1.02 \ €_{2012} \) (adapted nuclear S curve Europe)
Table of Contents

• Chapter 0  Objective / Terms of Study
• Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
• Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
• Chapter 3  Investment Cost of New NPPs
• Chapter 4  Investment Cost for Long-Term Operation (LTO)
• Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
• Chapter 6  Results LCOE of Nuclear Generation
• Chapter 7  External Costs / Externalities
• Chapter 8  Cost of Nuclear Accidents and Liability
• Chapter 9  System Costs
• Chapter 10  Overall Cost of Nuclear – Adding Things Together
• Chapter 11  Conclusions in Brief
**Recall:** Results for LCOE - NEA/IEA (2010)

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

<table>
<thead>
<tr>
<th>Country</th>
<th>Technology</th>
<th>Net capacity</th>
<th>Overight costs</th>
<th>Investment costs</th>
<th>Decommissioning costs</th>
<th>Fuel Cycle costs</th>
<th>O&amp;M costs</th>
<th>LCOE 5%</th>
<th>LCOE 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MWe</td>
<td>USD/kWe</td>
<td>USD/kWe</td>
<td>5%</td>
<td>10%</td>
<td>USD/MWh</td>
<td>USD/MWh</td>
<td>USD/MWh</td>
</tr>
<tr>
<td>Belgium</td>
<td>EPR-1600</td>
<td>1 600</td>
<td>5 383</td>
<td>6 185</td>
<td>7 117</td>
<td>0.23</td>
<td>0.02</td>
<td>9.33</td>
<td>7.20</td>
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<tr>
<td>Czech Rep.</td>
<td>PWR</td>
<td>1 150</td>
<td>5 858</td>
<td>6 392</td>
<td>6 971</td>
<td>0.22</td>
<td>0.07</td>
<td>9.33</td>
<td>14.74</td>
</tr>
<tr>
<td>France*</td>
<td>EPR</td>
<td>1 630</td>
<td>3 860</td>
<td>4 483</td>
<td>5 219</td>
<td>0.05</td>
<td>0.01</td>
<td>9.33</td>
<td>16.00</td>
</tr>
<tr>
<td>Germany</td>
<td>PWR</td>
<td>1 600</td>
<td>4 102</td>
<td>4 599</td>
<td>5 022</td>
<td>0.00</td>
<td>0.00</td>
<td>9.33</td>
<td>8.80</td>
</tr>
<tr>
<td>Hungary</td>
<td>PWR</td>
<td>1 120</td>
<td>5 198</td>
<td>5 632</td>
<td>6 113</td>
<td>1.77</td>
<td>2.18</td>
<td>8.77</td>
<td>29.79/29.84</td>
</tr>
<tr>
<td>Japan</td>
<td>ABWR</td>
<td>1 330</td>
<td>3 009</td>
<td>3 430</td>
<td>3 940</td>
<td>0.13</td>
<td>0.01</td>
<td>9.33</td>
<td>16.50</td>
</tr>
<tr>
<td>Korea</td>
<td>OPR-1000</td>
<td>954</td>
<td>1 876</td>
<td>2 098</td>
<td>2 340</td>
<td>0.09</td>
<td>0.01</td>
<td>7.90</td>
<td>10.42</td>
</tr>
<tr>
<td></td>
<td>APR-1400</td>
<td>1 343</td>
<td>1 566</td>
<td>1 751</td>
<td>1 964</td>
<td>0.07</td>
<td>0.01</td>
<td>6.08</td>
<td>8.95</td>
</tr>
<tr>
<td>Netherlands</td>
<td>PWR</td>
<td>1 650</td>
<td>5 105</td>
<td>5 709</td>
<td>6 383</td>
<td>0.20</td>
<td>0.02</td>
<td>9.33</td>
<td>13.71</td>
</tr>
<tr>
<td>Slovak Rep.</td>
<td>VVER 440/ V213</td>
<td>954</td>
<td>4 261</td>
<td>4 874</td>
<td>5 580</td>
<td>0.16</td>
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*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):


- 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

**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

Fuel Cycle Costs and O&M Costs

- **Overall Results**

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

  ![Graph showing fuel cycle costs for different scenarios and system sizes.](image)

  - Direct disposal route, total fuel cycle
  - Partial recycling in LWRs, total fuel cycle
  - Multiple Pu recycling with LWRs and FRs, total fuel cycle
  - Direct disposal route, back-end cost
  - Partial recycling in LWRs, back-end cost
  - Multiple Pu recycling with LWRs and FRs, back-end cost

  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

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% and 3% discount rates.

Total fuel cycle cost for a 75 TWh/year system, at 0% discount rate:
- Direct disposal route
- Partial recycling in LWR
- Multiple Pu recycling with LWRs and FRs

Total fuel cycle cost for a 75 TWh/year system, at 3% discount rate:
- Direct disposal route
- Partial recycling in LWR
- Multiple Pu recycling with LWRs and FRs

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

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

~ insensitive to discount rate!

Fuel Cycle Costs and O&M Costs

Comparison with other studies

Table 3.10 Summary of modelling results

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Units: $\textsubscript{2010}/\text{MWh}_e$


x/y total FC / back end
# Fuel Cycle Costs and O&M Costs

## Generic fuel cycle cost

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<th>System size</th>
<th>25 TWh/yr</th>
<th>400 TWh/yr</th>
<th>800 TWh/yr</th>
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</tr>
</tbody>
</table>

Units: $\text{2010/MWh}_e$  
\(x/y\) total FC / back end

Take as generic figure:  
Total fuel cycle cost \(\sim \frac{8}{2} \text{ $\text{2010 per MWh}_e} \)

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

Total fuel cycle cost \(\sim \frac{6.15}{1.55} \text{ €\text{2012 per MWh}_e} \)

**Generic order of magnitude fuel cycle cost**  
\(\sim \frac{6}{1.5} \text{ €\text{2012 per MWh}_e} \)

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 \(\varepsilon_{2012}\), central value was 6 \(\varepsilon_{2012} / \text{MWh}_e\)

- Hence estimate LCOE_{fuel}
  \(~ 6 \varepsilon_{2012} / \text{MWh}_e \ (\pm 0.75 \varepsilon_{2012} / \text{MWh}_e)\)
### Table 3.7a: Nuclear power plants: Levelised costs of electricity in US dollars per MWh

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<tr>
<th>Country</th>
<th>Technology</th>
<th>Net capacity</th>
<th>Overhead costs(^1)</th>
<th>Investment costs(^2) 5%</th>
<th>Investment costs(^2) 10%</th>
<th>Decommissioning costs 5%</th>
<th>Decommissioning costs 10%</th>
<th>Fuel Cycle costs</th>
<th>O&amp;M costs(^3) 5%</th>
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\(^*\)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 refurbishment 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} ≈ €_{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

- **Chapter 0**  Objective / Terms of Study
- **Chapter 1**  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- **Chapter 2**  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- **Chapter 3**  Investment Cost of New NPPs
- **Chapter 4**  Investment Cost for Long-Term Operation (LTO)
- **Chapter 5**  Fuel Cycle Costs and Operation & Maintenance (O&M)
- **Chapter 6**  Results LCOE of Nuclear Generation
- **Chapter 7**  External Costs / Externalities
- **Chapter 8**  Cost of Nuclear Accidents and Liability
- **Chapter 9**  System Costs
- **Chapter 10**  Overall Cost of Nuclear – Adding Things Together
- **Chapter 11**  Conclusions in Brief
LCOE computations

1) New Build

Parameters:

• Load Factor=85%;
• Operation Time $T=60\text{y}$;
• 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 €\textsubscript{2012} per MWh (± 0.75 €\textsubscript{2012} per MWh)

• LCOE O&M: 10 €\textsubscript{2012} per MWh (± 3.5 €\textsubscript{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:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>For NOAK$_2$ (5+) on a brownfield</td>
<td>3,060...3,400...3,910 $EUR_{2012}/kW$</td>
</tr>
<tr>
<td>For FOAK$_2$ twin unit on brownfield</td>
<td>3,128...3,910...5,083 $EUR_{2012}/kW$</td>
</tr>
<tr>
<td>For FOAK$_2$ single unit on brownfield</td>
<td>3,400...4,250...5,525 $EUR_{2012}/kW$</td>
</tr>
</tbody>
</table>
LCOE computations

- **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\%) \rightarrow \text{LCOE}_{LTO}(5\%) = 21\,\text{€}_{2012}/\text{MWh} \quad \& \quad \text{LCOE}_{LTO}(10\%) = 23\,\text{€}_{2012}/\text{MWh}
- ORC = 600 € (ref) \rightarrow \text{LCOE}_{LTO}(5\%) = 23\,\text{€}_{2012}/\text{MWh} \quad \& \quad \text{LCOE}_{LTO}(10\%) = 26\,\text{€}_{2012}/\text{MWh}
- ORC = 850 € (ref + 42\%) \rightarrow \text{LCOE}_{LTO}(5\%) = 26\,\text{€}_{2012}/\text{MWh} \quad \& \quad \text{LCOE}_{LTO}(10\%) = 30\,\text{€}_{2012}/\text{MWh}

All results \pm 4.25 \,\text{€}_{2012}/\text{MWh} \text{ (fuel cycle and O&M)}
Table of Contents

• Chapter 0  Objective / Terms of Study
• Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
• Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
• Chapter 3  Investment Cost of New NPPs
• Chapter 4  Investment Cost for Long-Term Operation (LTO)
• Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
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• Chapter 7  External Costs / Externalities
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• Chapter 9  System Costs
• Chapter 10 Overall Cost of Nuclear – Adding Things Together
• Chapter 11 Conclusions in Brief
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)
- 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)
    - $T < 30a, r=5\% \text{ and } T>31a, r = 2\%$
  - Oxera, UK (2002)
    - $T < 30a, r=3.5\% \text{ and } 75a>T>31a, r = 3\%$
    - $125a>T>76a, r = 2.5\% \text{ ... and } T>300a, r=1\%$
  - Lebégue, FR (2005) – for all public investments
    - $T < 30a, r=4\% \text{ ...continuously... } T=100a, r = 3\%$
    - $...continuously... \text{ } T=200a, r = 2\%$
- **Other references:** public policy appraisal ST ~ 3 - 4% LT ~ 0 - 1%
Some published values: “routine operation” / no accidents

Again: orders of magnitude estimates!

  - 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)
  - 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

Full costs of energy production for nuclear and thermal technologies (2005-2010)

Ref: CASES, Deliverable 6.1, 2008, p 16 – No accidents included
External Costs / Externalities

Ref: IER, Stuttgart (2013)
# Table of Contents

- Chapter 0  Objective / Terms of Study
- Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- Chapter 3  Investment Cost of New NPPs
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- Chapter 6  Results LCOE of Nuclear Generation
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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”:
  \[ \text{Risk} = \text{Probability} \times \text{Effect} \]

• External cost due to a nuclear accident:
  \[ \text{Expected Cost} = (\text{Probability accident}) \times (\text{Cost accident}) \]
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 ~ $8 \times 10^{-4} - 0.35$ €/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 $\rightarrow$ x 100 $\rightarrow$ $10^{-5}$/react-a
     • Typical damage ~100 G€ $\rightarrow$ x 10 $\rightarrow$ $10^{12}$ €
     • Risk = $10$ M€/react-a
     • Production typical reactor in 1 year $\sim$ 10 TWh/a
     • Estimated external cost accident $\sim$ 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) $\rightarrow 7.8 \times 10^{-4}$/react-a
     - for theoretical prob = $6.5 \times 10^{-5}$/react-a
     - result Bayesian ‘magic’ $\rightarrow 3.2 \times 10^{-4}$/react-a
     - but (WDH): this was for 11 ‘accidents’ and CDF, not LERF
       $\rightarrow$ result is at least factor 10 smaller $\rightarrow 2 \times 10^{-5}$/react-a

For damage of $\sim 500$ G€ and practical LERF= $2 \times 10^{-5}$/react-a,

$\rightarrow$ external cost accident of indeed $\sim 1$ €/MWh
Cost of Nuclear Accidents & Liability

Summary cost Nuclear Accidents:

~ 0.3... 1 ...3 €/MWh
Cost of Nuclear Accidents & Liability

![Cost of Nuclear Accidents & Liability](image)

Abbildung 6: Schadenskosten der Kernenergie im Vergleich mit anderen Stromerzeugungstechnologien

Ref: [IER, 2013]

Total external cost now with accidents; accidents invisible...
Table of Contents

• Chapter 0  Objective / Terms of Study
• Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
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• Chapter 6  Results LCOE of Nuclear Generation
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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 |
|---|---|---|
| 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 |

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 penet**

<table>
<thead>
<tr>
<th>Total cost of electricity supply (USD/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference</strong></td>
</tr>
<tr>
<td>Conv. mix</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Total cost of electricity supply</td>
</tr>
<tr>
<td>Increase in plant-level cost</td>
</tr>
<tr>
<td>Grid-level system costs</td>
</tr>
<tr>
<td>Cost increase</td>
</tr>
</tbody>
</table>

*Note: Values are approximate and may vary depending on specific conditions and locations.*
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

<table>
<thead>
<tr>
<th>Installed capacities of nuclear power plants/share of renewables</th>
<th>(EUR/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 GW</td>
</tr>
<tr>
<td>15%</td>
<td>95</td>
</tr>
<tr>
<td>35%</td>
<td>120</td>
</tr>
<tr>
<td>50%</td>
<td>132</td>
</tr>
<tr>
<td>80%</td>
<td>174</td>
</tr>
</tbody>
</table>

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

- Chapter 0  Objective / Terms of Study
- Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
- Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
- Chapter 3  Investment Cost of New NPPs
- Chapter 4  Investment Cost for Long-Term Operation (LTO)
- Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
- Chapter 6  Results LCOE of Nuclear Generation
- Chapter 7  External Costs / Externalities
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- **Chapter 10**  Overall Cost of Nuclear – Adding Things Together
- Chapter 11  Conclusions in Brief
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%)  \[\rightarrow LCOE_{LTO}(5\%) = 21\text{	extcurrency}_2012/MWh\]  \&  \[LCOE_{LTO}(10\%) = 23\text{	extcurrency}_2012/MWh\]
- ORC = 600 € (ref)  \[\rightarrow LCOE_{LTO}(5\%) = 23\text{	extcurrency}_2012/MWh\]  \&  \[LCOE_{LTO}(10\%) = 26\text{	extcurrency}_2012/MWh\]
- ORC = 850 € (ref + 42%)  \[\rightarrow LCOE_{LTO}(5\%) = 26\text{	extcurrency}_2012/MWh\]  \&  \[LCOE_{LTO}(10\%) = 30\text{	extcurrency}_2012/MWh\]

Uncertainty of $\pm 4 \text{	extcurrency}_2012/MWh$
External Costs

Without Accidents

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

- Compare with other means
  - Coal: ~ 40 €\textsubscript{2012}/MWh
  - Gas: ~ 20 €\textsubscript{2012}/MWh
  - PV: ~ 10 €\textsubscript{2012}/MWh
  - Wind: ~ 2 €\textsubscript{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**

<table>
<thead>
<tr>
<th>Total cost of electricity supply (USD/MWh)</th>
<th>Reference</th>
<th>10% penetration level</th>
<th>30% penetration level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conv. mix</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind onshore</td>
<td>80.7</td>
<td>86.6</td>
<td>91.3</td>
</tr>
<tr>
<td>Wind offshore</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar</td>
<td>101.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wind onshore</strong></td>
<td>105.5</td>
<td>116.9</td>
<td>156.2</td>
</tr>
<tr>
<td>Wind offshore</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar</td>
<td>30% penetration level</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total cost of electricity supply</strong></td>
<td>80.7</td>
<td>86.6</td>
<td>91.3</td>
</tr>
<tr>
<td>Increase in plant-level cost</td>
<td>-</td>
<td>3.9</td>
<td>7.8</td>
</tr>
<tr>
<td>Grid-level system costs</td>
<td>-</td>
<td>1.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Cost increase</td>
<td>-</td>
<td>5.8</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**Germany**

- Increase in plant-level cost
- Grid-level system costs
- Cost increase
## Overall Cost - Summary

**System Costs – Integrated model DE**

<table>
<thead>
<tr>
<th>Installed capacities of nuclear power plants/share of renewables</th>
<th>(EUR/MWh)</th>
<th>0 GW</th>
<th>20.7 GW</th>
<th>41.4 GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%</td>
<td>95</td>
<td>84</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>35%</td>
<td>120</td>
<td>109</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>132</td>
<td>122</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td>174</td>
<td>171</td>
<td>174*</td>
<td></td>
</tr>
</tbody>
</table>

*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

• Chapter 0  Objective / Terms of Study
• Chapter 1  Context & Setting the Scene - The Different Cost Elements of Nuclear Generated Electricity
• Chapter 2  Definitions, Conventions, Boundary Conditions, Hypotheses; Important Issues
• Chapter 3  Investment Cost of New NPPs
• Chapter 4  Investment Cost for Long-Term Operation (LTO)
• Chapter 5  Fuel Cycle Costs and Operation & Maintenance (O&M)
• Chapter 6  Results LCOE of Nuclear Generation
• Chapter 7  External Costs / Externalities
• Chapter 8  Cost of Nuclear Accidents and Liability
• Chapter 9  System Costs
• Chapter 10  Overall Cost of Nuclear – Adding Things Together
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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 & modelling assumptions)

But overall, nuclear is affordable low-CO\textsubscript{2} electricity means!