Cost Estimates and Economics of Nuclear Power Plant Newbuild: Literature Survey and Some Modelling Analysis

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Agenda

1) Introduction
2) Nuclear Power Economics
3) Historical and current construction projects
4) The perspectives for nuclear power
5) Conclusion and Outlook
Looking back …

…no-one ever pretended nuclear was „economic“ …

MIT (2003, p. 3): The Future of Nuclear Power

“In deregulated markets, nuclear power is not now cost competitive with coal and natural gas.”

University of Chicago (2004, p. 5-1):

“A case can be made that the nuclear industry will start near the bottom of its learning rate when new nuclear construction occurs. (p. 4-1) … “The nuclear LCOE for the most favorable case, $47 per MWh, is close but still above the highest coal cost of $41 per MWh and gas cost of $45 per MWh.”

Parsons/Joskow (EEEP 2012)

“may be one day …”

D’haeseleer (2013, p. 3): Synthesis on the Economics of Nuclear Energy

“Nuclear new build is highly capital intensive and currently not cheap, … it is up to the nuclear sector itself to demonstrate on the ground that cost-effective construction is possible.” (p. 3)


“These external costs are in addition to substantial private costs. In 1942, with a shoestring budget in an abandoned squash court at the University of Chicago, Enrico Fermi demonstrated that electricity could be generated using a self-sustaining nuclear reaction.

Seventy years later the industry is still trying to demonstrate how this can be scaled up cheaply enough to compete with coal and natural gas.“ (p. 63)
None of the 674 reactors analysed in the text and documented in the appendix, has been developed based on what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system. Given current technical and economic trends in the global energy industry, there is no reason to believe that this rule will be broken in the near- or longer-term future.
The perspectives of nuclear power deployment depend in the long term on...

... the development of costs, in relation to other low-carbon options, and the economics of investments into new capacities.

While there is a consensus in the literature that nuclear power is not competitive under regular market economy, competitive conditions, at least two issues need to be considered going forward:

First, the treatment of “costs” in other, non-market institutional contexts:
• such as indigenous suppliers or “home suppliers” (Thomas, 2010),
• or the subsidized export models of countries like China (Thomas, 2017) or Russia (Hirschhausen, 2017).

Second, the evolution of future technologies (e.g., Gen III/III+, Gen IV, SMR).
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The most used indicator for comparing different generation technologies is the cost concept of “overnight construction costs” (OCC), i.e. as if the full expenditure were spent “overnight”, therefore the interest during construction is not included (i.e. financing cost).

<table>
<thead>
<tr>
<th>Cost Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner's cost</td>
</tr>
<tr>
<td>+ Engineering, Procurement, and</td>
</tr>
<tr>
<td>+ Construction costs (EPC)</td>
</tr>
<tr>
<td>+ Contingency Provision</td>
</tr>
<tr>
<td>= Overnight construction cost</td>
</tr>
<tr>
<td>+ Interest during Construction (IDC)</td>
</tr>
<tr>
<td>= (Total) Investment Cost (TIC)</td>
</tr>
</tbody>
</table>

Source: Own depiction based on D’Haeseleer (2013)
Systematic View of a nuclear power plant

One can also break down capital costs into direct costs according more or less to different systems of a nuclear power plant. Indirect costs include construction services, engineering & home office services, and field supervision & field office services.

Source: Own depiction based on Rothwell (2016) and NRC 10 CFR §170.3
## Cost breakdown for a Westinghouse AP1000

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures &amp; improvements</td>
<td>460</td>
<td>403</td>
<td>863</td>
<td>20%</td>
</tr>
<tr>
<td>Reactor equipment</td>
<td>575</td>
<td>726</td>
<td></td>
<td>40%</td>
</tr>
<tr>
<td>Turbine generator equipment</td>
<td>288</td>
<td>484</td>
<td>1,693</td>
<td>25%</td>
</tr>
<tr>
<td>Cooling system and miscellaneous equipment</td>
<td>115</td>
<td>94</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>173</td>
<td>202</td>
<td>314</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Total direct, DIR</strong></td>
<td><strong>1,611</strong></td>
<td><strong>1,906</strong></td>
<td><strong>2,870</strong></td>
<td></td>
</tr>
<tr>
<td>Capitalised indirect costs, INDIR</td>
<td>460</td>
<td>258</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capitalised owner’s costs, OWN</td>
<td>0</td>
<td>322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplementary costs, SUPP</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base overnight cost, BASE</strong></td>
<td><strong>2,071</strong></td>
<td><strong>2,487</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contingency rate</td>
<td>9%</td>
<td>16%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overnight cost, OC</td>
<td>2,261</td>
<td>2,875</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IDC factor, idc</td>
<td>14%</td>
<td>25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total construction cost, KC</strong></td>
<td><strong>2,577</strong></td>
<td><strong>3,601</strong></td>
<td><strong>5,945</strong></td>
<td></td>
</tr>
</tbody>
</table>

Source: Own depiction based on Rothwell (2016)
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Nuclear power plants are historically characterized by high construction costs

The low historical costs in France illustrate the impacts of different institutional settings. Grubler (2010, p. 5185) argues that “the “central planning” model in France with its regulatory stability and unified, nationalized, technically skilled principal-agent (EDF) appears economically more successful […], than the more decentralized, market-oriented, but regulatorily uncertain (and multi-layered, i.e. state and federal) US system.”

The Gen I and Gen II reactors were mainly constructed by integrated “home suppliers”.

Comparison of French and US construction costs in 1994 USD
Source: Grubler (2010)
## Current construction projects (in 2017): 54 NPPs or 52 GW in 13 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Construction capacity in MW (NPP)</th>
<th>Technologies</th>
<th>Generation</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>25 (1)</td>
<td>Carem25</td>
<td>SMR</td>
<td>Argentina</td>
</tr>
<tr>
<td>Belarus</td>
<td>2,218 (2)</td>
<td>VVER V-491</td>
<td>Gen III⁺ (2)</td>
<td>Atomstroyexport</td>
</tr>
<tr>
<td>China</td>
<td>19,500 (19)</td>
<td>ACPR-1000, HPR-1000, HTR-PM, VVER V-428M, AP-1000, EPR</td>
<td>Gen III (13), Gen III⁺ (6)</td>
<td>China, cooperation with Toshiba, Areva, and Atomstroyexport</td>
</tr>
<tr>
<td>Finland</td>
<td>1,600 (1)</td>
<td>EPR</td>
<td>Gen III⁺</td>
<td>Framatome</td>
</tr>
<tr>
<td>France</td>
<td>1,600 (1)</td>
<td>EPR</td>
<td>Gen III⁺</td>
<td>Framatome</td>
</tr>
<tr>
<td>India</td>
<td>3,907 (6)</td>
<td>PHWR-700, VVER-1000, Prototype FBR</td>
<td>Gen II (4), Gen III (1), Other (1)</td>
<td>Indian, Atomstroyexport</td>
</tr>
<tr>
<td>Japan</td>
<td>2,650 (2)</td>
<td>ABWR</td>
<td></td>
<td>Hitachi-GE</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2,028 (2)</td>
<td>ACP-1000</td>
<td></td>
<td>China</td>
</tr>
<tr>
<td>Russia</td>
<td>4,359 (7)</td>
<td>VVER V-320, VVER V-392 M, VVER V-491, KLT-40S</td>
<td>Gen II (1), Gen III⁺ (4), Other (2)</td>
<td>Russia</td>
</tr>
<tr>
<td>Slovakia</td>
<td>880 (2)</td>
<td>VVER V-213</td>
<td>Gen III⁺</td>
<td>Atomstroyexport</td>
</tr>
<tr>
<td>South Korea</td>
<td>5,360 (5)</td>
<td>APR-14000</td>
<td>Gen III</td>
<td>KEPCO (South Korea)</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>5,380 (4)</td>
<td>APR-14000</td>
<td>Gen III</td>
<td>KEPCO (South Korea)</td>
</tr>
<tr>
<td>USA</td>
<td>2,234 (2)</td>
<td>AP1000</td>
<td>Gen III⁺</td>
<td>Westinghouse</td>
</tr>
<tr>
<td></td>
<td><strong>51,741 (54)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Own depiction, for more details see Wealer et al. (2018, p. 32)
Gen III/III+ reactor vendors and the nuclear supply chain I/II

The low construction orders have put the traditional reactor vendors in serious financial troubles:

• **Westinghouse** filed Chapter 11 bankruptcy protection in the US. and was acquired by Brookfield Business Partners for 4.6 billion USD from Toshiba Corporation in January 2018.

• Going forward **Toshiba** is considering the withdrawal of all nuclear projects (Schneider et al., 2017, pp. 144–145).

• **Hitachi** has never exported a reactor and its recent technology the ABWR has been proven as unreliable (Thomas, 2017b).

• **Areva**: In 2017, Areva has been forced to split up and the reactor division Areva NP was sold to EDF for 2.5 billion EUR and was renamed Framatome, the company got injected with a 5 billion EUR capital increase—4.5 billion EUR stemming from the French state (Schneider et al., 2017, pp. 136–137).
Gen III/III+ reactor vendors and the nuclear supply chain II/II

Today, the production of large components will generally be subcontracted to specialist companies and built on a one-off basis, presumably at higher costs in countries such as Japan and China.

The supply chain for Gen III/III+ the reactor pressure vessel is the most constrained. The two major (of 5) very heavy forging capacities in operation today are:

• Japan Steel Works (JSW) (80% of the world market share): EPR for Finland was entirely manufactured by JSW. In 2009, Westinghouse was already constrained as reactor and steam generator parts could only be delivered by JSW (World Nuclear Association, 2017).

• Le Creusot in France, part of the Areva Group since 2006, has been in hot water in recent times and is currently being investigated due to irregularities in quality-control documentation and manufacturing defects of forged pieces produced for the EPR as well as the operational reactors, leading to multiple shutdowns in 2016.
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Some cost estimates for Gen III/III+ reactors in the US and Europe and cost estimates for ongoing new build projects

Cost estimations have to be regarded critically, as no Gen III/III+ reactors has been successfully connected to the grid in the US or Europe. As always all these cost figures omit costs for decommissioning and waste disposal.

Source: Own depiction
Davis (2012; JEP, p. 11): „70 years later …“ current update for Europe (own calc.)

**Table 3**

**Levelized Cost Comparison for Electricity Generation**

<table>
<thead>
<tr>
<th>Source</th>
<th>Nuclear</th>
<th>Coal</th>
<th>Natural gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT (2009) baseline</td>
<td>8.7</td>
<td>6.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Updated construction costs</td>
<td>10.4</td>
<td>7.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Updated construction costs and fuel prices</td>
<td>10.5</td>
<td>7.4</td>
<td>5.2</td>
</tr>
<tr>
<td>With carbon tax of $25 per ton CO₂</td>
<td>10.5</td>
<td>9.6</td>
<td>6.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Nuclear</th>
<th>Coal</th>
<th>Natural gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (2016)</td>
<td>11</td>
<td>5.1</td>
<td>5.0</td>
</tr>
<tr>
<td>CO₂-price: 25 €/t</td>
<td>11</td>
<td>6.3</td>
<td>5.7</td>
</tr>
<tr>
<td>CO₂-price: 100 €/t</td>
<td>11</td>
<td>10.0</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Source: own calculation
Nuclear power – profitability check

General assumptions:

• Investment
  • Overnight cost: 6,000 €/kW
  • Installed capacity: 1,100 MW
  • Initial investment: 20 years
  • Plant lifetime: 50 years

• Fixed and variable costs
  • Fixed operating costs:
    • Operation 20 €/kW/year
    • Maintenance 20 €/kW/year
    • Insurance 15 €/kW/year
  • Variable operating costs:
    • Operation 8 €/MWhel
    • Maintenance 7 €/MWhel
  • Fuel price: 1,5 €/MWhth
  • Electric efficiency: 38%
  • Full load hours: 6,500 h

Calculation results:

- Nuclear power is more expensive than competing technologies
- Levelized cost of electricity generation:
  - 11 cent/kWh
- Assumed electricity retail price:
  - 40 €/MWh
- Net present value very negative:
  - –13 bn €
- To reach NPV = 0:
  - Retail price: ~100€/MWh
Nuclear power – profitability check monte carlo analysis

Monte carlo parameters

- Wholesale electricity price: 30 to 50 €/MWh
- Investment cost: 4,500 to 7,500 €/kW
- Debt capital interest rate: 5% to 10%
- Equity capital interest rate: 2% to 10%

Monte carlo results
Variation of Investment cost and retail price

Investment cost in €/kW vs. Retail price in €/MW vs. NPV (Million €)

-20,000 € ≤ NPV ≤ 20,000 €

-20,000 € ≤ Retail price in €/MW ≤ 78,000 €

-20,000 € ≤ Investment cost in €/kW ≤ 7500 €
Looking forward...
...Gen IV no option for the foreseeable future (although prototypes exist)

Source: IAEA
…neither are „Small modular reactors“ (SMRs)…

The concept of SMRs has been around since the dawn of the nuclear age.

No SMR has ever been operated and current projects (if not abandoned) suffer from serious delays – both in construction and reactor design.

In sum, economic viability of SMRs is not clear and no option any private investor would seek; potential scale economies must be weighed against technical risks and higher proliferation risks.

GenIV reactors are only partially based on fundamentally different designs, as FBRs, HTR, thorium concepts are around since the 1950s.

Deployment seems far from certain due to even higher capital costs than Gen III+ reactors.

Another plea for Gen IV reactors is proliferation resistance, this is not the case, e.g. Gen IV reactors all have a closed fuel cycle, plutonium as fuel…

…leading to no short-term prospects for Gen IV and SMRs
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Conclusion: Nuclear power is not competitive

Looking back no-one ever pretended nuclear was „economic“. 

Investment costs for NPPs have significantly increased in the western hemisphere over the last decades.

Due to increased market competition and the disappearance of large vertically integrated utilities, there is no guarantee that market prices will be high enough to cover costs, e.g., investment and interest costs.

Traditional reactor vendors: in financial troubles and tainted technologies.

Supply chain for the reactor pressure vessel is constraint.

Decommissioning cost of about 1,000 €/kW are neglected most of the time and further reduce profitability.

Comparing the LCOE of nuclear power plants to other renewable and fossil technologies, competitiveness is far from being in sight.

If Russia and China are able to provide the role of a global supplier needs to be seen, but both countries provide a strong government backed package including financing as a policy tool.
References (selection)


References (selection)


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Thank you for your attention!

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