Decommissioning of Nuclear Power Plants: International Comparison of Organisational Models and Policy Perspectives

Ben Wealer (WIP/DIW)
Agenda

1) Introduction

2) Nuclear Power Economics

3) Decommissioning of Nuclear Power
   1) Global Survey
   2) France
   3) United States of America
   4) Germany
   5) Japan

4) Conclusion and Outlook
Francois Lévêque (2013): „L’énergie atomique est la fille de la science et de la guerre“

Durchschnittliche Energieverteilung für die Spaltung des $^{235}_{92}$U-Kerns in MeV:

$^{235}_{92}$U + $^1_0$n → $^{236}_{92}$U → $^{89}_{36}$Kr + $^{144}_{56}$Ba + 3 $^1_0$n

Ausgangs- thermisches hier
kern Neutron hier
(Spalt- Zwischen- Krypton
stoff) Produkt Barium

$3 \cdot 10^{18}$ Spaltungen/s ≈ 1 W
1 kg Uran ≈ 3000 t Steinkohle

$\gamma$-Strahlung $\sim 5$ MeV
kinetische $\sim 170$ MeV $\sim 5$ MeV $\sim 20$ MeV
$\beta+\gamma$-Strahlung $\sim 180$ MeV
$\sim 200$ MeV/Spaltung
None of the 674 or so 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.
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3) Decommissioning of Nuclear Power
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)
The perspectives of nuclear power deployment depend in the long term on…

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).
Capital Costs of Nuclear Power – Different Cost Levels

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 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)
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>
<th></th>
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<th></th>
<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)
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.
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.
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

\[
NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]
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

![Monte Carlo Results Graph]

Probability

0.025

0.02

0.015

0.01

0.005

0.0025

NPV

-11,054,636...

-10,341,390...

-9,913,442...

-9,770,793...

-9,628,144...

-9,485,494...

-9,342,845...

-9,191,206...

-8,949,567...

-8,708,928...

-8,468,289...

-8,227,650...

-7,987,011...

-7,746,372...

-7,505,733...

-7,265,094...

-7,024,455...

-6,783,816...

-6,543,177...

-6,302,538...

-6,061,899...

-5,821,260...

-5,580,621...

-5,339,982...

-5,099,343...

-4,858,704...

-4,618,065...

-4,377,426...

-4,136,787...

-3,896,148...

-3,655,509...

-3,414,870...

-3,174,231...

-2,933,592...

-2,692,953...

-2,452,314...

-2,211,675...

-1,971,036...

-1,730,397...

-1,490,758...

-1,251,119...

-1,011,480...

-771,841...

-532,202...

-292,563...

0
Variation of Investment cost and retail price

Investment cost in €/kW

Retail price in €/MW

NPV

Million

0 €
-2,000 €
-4,000 €
-6,000 €
-8,000 €
-10,000 €
-12,000 €
-14,000 €
-16,000 €
-18,000 €
-20,000 €

2,000 €

30,000 €

26,000 €

22,000 €

18,000 €

14,000 €

10,000 €

6,000 €

2,000 €

0 €
Looking forward…
…Gen IV no option for the foreseeable future (although prototypes exist)

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

...leading to no short-term prospects for Gen IV and 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...
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4) Conclusion and Outlook
The Decommissioning Status Report in WNISR (2018)

Since 2018 the World Nuclear Industry Status Report (WNISR) includes a chapter on decommissioning:

“The Decommissioning Status Report”

Lead Authors: Mycle Schneider and Antony Froggatt

With: Julie Hazeman, Tadahiro Katsuta, Andy Stirling, Phil Johnstone, M.V. Ramana, Agnès Stienne, Christian von Hirschhausen, and Ben Wealer

The following presentation is largely based on the WNISR (2018).

Outlook – Global Development of the Nuclear Power Plant Fleet

Source: Authors, based on IAEA (2017) PRIS Database

As of 1 July 2018: 173 permanently shut down reactors, or 74 GW of capacity.
By 2030: a further 216 reactors will shut down (grid connection: 1978-90).
By 2057: additional 111 will be shut down.
Not accounting for 81 operational reactors (grid connection before 1978), and additional 33 reactors in long-term outage (LTO).
Decommissioning refers to the administrative and technical actions taken to remove all or some of the regulatory controls from an authorized facility so the facility and its site can be reused. Decommissioning includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management. - IAEA

5-Stage-Classification

1) Peripheral Systems
2) Machinery and higher contaminated parts
3) RPV and biological shield
4) Remaining contaminated systems
5) Greenfield or further proceedings of the building

3-Stage-Classification

- Warm-up-Stage: Measures prior to the treatment of the hot zone
- Hot-zone-Stage: Removal of the RPV and biological shield
- Ease-off-Stage: Measures to release site from regularly control

Standard Procedures of Decommissioning

Warm-up-Stage

- Defueling the reactor
- Overview of all radioactive inventory
- Removal of **peripheral parts and machinery**, that are not needed during the decommissioning phase
- Set up of a technical and logistical infrastructure for the decommissioning project

**Defueling** of the reactor core is a prerequisite of decommissioning

On-site transport of SNF

Image: GSR (2017)

Spent fuel pool

Image: GSR (2017)
Standard Procedures of Decommissioning

**Warm-up-Stage**

- Deconstruction and dismantling of higher contaminated parts, e.g. the steam generator
- Preparations for the dismantling of highly contaminated (or activated), large scale parts

Decontamination through sandblasting

Image: GSR (2017)
Standard Procedures of Decommissioning

Hot-Zone-Stage

- Deconstruction and dismantling of highly contaminated parts e.g. RVP, biological shield

Remote controlled underwater cutting

One-piece removal

Image: GSR (2017)
Standard Procedures of Decommissioning

Ease-off-Stage

- Deconstruction and dismantling remaining parts and machinery
- **Decontamination** of the buildings

Markings for surface decontamination

- Release from regulatory control

Measurements for release
Standard Procedures of Decommissioning

Ease-off-Stage

- Demolishing of the buildings
  - **Greenfield**: No further nuclear related purpose of the site
  - **Brownfield**: Further “generation use” (e.g. gas turbine) or further nuclear related uses of the site, e.g. (interim) storage facility for nuclear waste

Images: GSR (2017)
### Possible Strategies of Decommissioning

<table>
<thead>
<tr>
<th>Strategy</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
</table>
| IMMEDIATE DISMANTLING (ID)     | • Skill and expertise of the operating staff is key for decommissioning  
   • Clear line of responsibilities  
   • High public interest  
   • More financial security | • High safety precautions due to high intensity of radiation  
   • Larger volumes of radioactive waste  
   • Lack of motivation of the workforce |
| LONG TERM ENCLOSURE (LTE) or   | • Lower intensity of radiation due to radioactive decay  
   DEFERRED DISMANTLING (DD)   | • Risk of losing  
   • trained staff and knowledge about the facility  
   • clear lines of responsibilities  
   • public interest  
   • Risk of bankruptcy or other financial trouble of the company in charge |
| ENTOMBMENT                     | • Relatively easy to realize                                     | • *Out of sight, out of mind*: no dismantling of the reactor  
   • Unpredictable risks  
   • Constant occupation over a long period requires staff and financial stamina |
## Organizational models for decommissioning (and radioactive waste management)

<table>
<thead>
<tr>
<th>Production</th>
<th>A) Public enterprise</th>
<th>B) Private enterprise (decentral or status quo)</th>
<th>C) Public tender (centralized or decentralized)</th>
<th>D) Further Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Public budget</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) External segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Internal non segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Internal segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) Further Alternatives</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Seidel and Wealer (2016), based on Klatt (2011)
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1) Global Survey
2) France
3) United States of America
4) Germany
5) Japan
4) Conclusion and Outlook
Global Survey

In the first quarter of 2018 154 units were globally undergoing (in various stages) or awaiting decommissioning.

D&D of the 19 NPPs (6 GW) was completed on average 16 years after shutdown.

Only 10 sites have been returned to a greenfield.

The only countries to have completed the decommissioning process are the United States (13), Germany (5), and Japan (1).

<table>
<thead>
<tr>
<th>Country</th>
<th>Shut-down reactors</th>
<th>Decommissioning Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Warm-up</td>
</tr>
<tr>
<td>Canada</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>France</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Germany</td>
<td>29</td>
<td>10</td>
</tr>
<tr>
<td>Japan</td>
<td>25</td>
<td>203a</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>United States</td>
<td>34</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>136</td>
<td>37</td>
</tr>
</tbody>
</table>

a - Not including the Fukushima Daini 1-4 reactors.

Sources: Various, compiled by WNI5R, 2018
Overview of Completed Decommissioning Projects, 1953 - 2017

Overview of Completed Reactor Decommissioning Projects, 1953-2017
in the U.S., Germany and Japan

United States
Shippingport
Yankee NPS
Elk River
Pathfinder
Saxton
CVTR
Big Rock Point
Haddam Neck
Fort St. Vrain
Maine Yankee
Rancho Seco-1
Trojan
Shoreham
VAK Kahl

Germany
Gundremmingen-A (KRB A)
HDR Grosswalzheim
Niederaichbach (KKN)
Wuergassen (KWW)

Japan
JPDR

Construction Commercial Operation Decommissioning

Source: WNISR and IAEA-PRIS, 2018
Agenda

1) Introduction
2) Nuclear Power Economics
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   1) Global Survey
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4) Conclusion and Outlook
Key Findings in France

12 reactors (8 GCR UNGG, 1 HWGCR, 2 FBR, 1 PWR) were shut down.

While EDF operates 57 PWRs (1 in LTO), the legacy fleet consists mainly of GCRs.

French Regulation stipulates Immediate Dismantling (ID).

EDF’s strategy shift in 2016: Decommissioning start of the first GCR Chinon A-1 in 2031 as an example for future GCR projects. LTE is de facto applied for 6 GCRs to await decommissioning.

In addition, there is not even a theoretical disposal route for graphite.

Only one PWR (Chooz-A) undergoing decommissioning. Since 2014, first underwater dismantling of an RPV.

9 reactors are the scope of EDF, 3 CEA.

Decommissioning monies are managed in internal segregated funds.

<table>
<thead>
<tr>
<th>France</th>
<th>May 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Warm-up-stage”</td>
<td>3</td>
</tr>
<tr>
<td>of which defueled</td>
<td>2</td>
</tr>
<tr>
<td>“Hot-zone-stage”</td>
<td>1</td>
</tr>
<tr>
<td>“Ease-off-stage”</td>
<td>0</td>
</tr>
<tr>
<td>LTE</td>
<td>8</td>
</tr>
<tr>
<td>Finished</td>
<td>0</td>
</tr>
<tr>
<td>of which greenfield</td>
<td>0</td>
</tr>
<tr>
<td>Shut-down reactors</td>
<td>12</td>
</tr>
</tbody>
</table>

Sources: Various, compiled by WNISR 2018
Organizational Challenges: Underprovisioning, long time horizons

Current cost estimates for EDFs shut-down fleet are around €6.5 billion, while EDF has only set aside €3.3 billion.

The costs for the legacy fleet have increased steadily and doubled since 2001, when they were estimated to be around €3.3 billion.

For the operational fleet EDF expects total costs of around €23 billion, which corresponds to around €300/kW of installed capacity, quite low by international standards.

In a recent report on the technical and financial feasibility of the decommissioning process, the French National Assembly alleged that EDF shows “excessive optimism”. The report concluded that decommissioning and clean-up will take more time, that the technical feasibility is not fully assured, and that the process will cost overall much more than EDF anticipates.

EDF’s new strategy aims to release the GCRs from regulatory control only by the beginning of the 22nd century.
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Key Findings in the United States of America

Operators can chose ID, LTE (up to 60 years), or Entombment.

Average decommissioning period of 14 years. 8 reactors were decommissioned under 10 years (removal of RPV as whole).

Strategy to remove large components in one piece in the Hot-Zone.

Possible use of explosives to demolish concrete buildings.

High cost variance: US$280/kW (Trojan) to US$1,500/kW (Connecticut Yankee)


The site license might be reduced to the Independent Spent Fuel Storage Installation.

<table>
<thead>
<tr>
<th>United States of America</th>
<th>May 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Warm-up-stage” of which defueled</td>
<td>4</td>
</tr>
<tr>
<td>“Hot-zone-stage”</td>
<td>0</td>
</tr>
<tr>
<td>“Ease-off-stage”</td>
<td>5</td>
</tr>
<tr>
<td>LTE</td>
<td>12a</td>
</tr>
<tr>
<td>Finished of which greenfield</td>
<td>6</td>
</tr>
<tr>
<td>Shut-down reactors</td>
<td>34</td>
</tr>
</tbody>
</table>

Source: WNISR (2018)
US nuclear power reactor grid connections and permanent shutdowns (1957 – 2050)

Source: Wealer et al. (2017)
New development: transfer decommissioning license from the operator to a waste management company

Zion-1 and -2 in Illinois: Exelon transferred the license to EnergySolutions.

Goal: reap efficiency gains through the (co-)management of the decommissioning process by a company owning disposal facilities.

Vermont Yankee: U.S. company Northstar has entered into a purchase and sale agreement with Entergy. The deal would include the transfer of the decommissioning trust of US$571 million (Entergy has promised to add another US$125 million). Entergy and Northstar are proposing this model also for the Pilgrim, Indian Point and Palisades stations.

These developments are problematic as limited-liability companies are only financially liable in the case of an accident or other legal dispute up to the value of their assets.

Therefore, if the decommissioning funds are exhausted, such a third-party company could declare bankruptcy, leaving the bill for the taxpayer.

Overall, there is an increasing risk, that the NDT will not be sufficient to cover the costs (outdated NRC-formula based on studies between 1978 and 1980).
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Key Findings in Germany

Immediate Dismantling was the most applied strategy - now set by law.

EUR 6.5 billion bill for the state only for the decommissioning of the 6 Soviet reactors of the former GDR (currently in EOS but deferred dismantling).

EUR 19.7 billion estimated costs for decommissioning in 2014 set aside in internal non-segregated funds.

The utilities are still responsible for decommissioning and for the conditioning of waste, but all the downstream tasks (mainly storage) will be done by public companies and paid from the waste fund.

Only 3 reactors (140 MW) have been released from regulatory control.

Gundremmingen-A (2.2bn latest cost est.) and Würgassen (1bn €) de facto decommissioned.

<table>
<thead>
<tr>
<th>Germany</th>
<th>2015</th>
<th>May 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Warm-up-stage” of which defueled</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>“Hot-zone-stage”</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>“Ease-off-stage”</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>LTE</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Finished of which greenfield</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Shut-down reactors</td>
<td>28</td>
<td>29</td>
</tr>
</tbody>
</table>

Source: Seidel and Wealer, 2016 and Bredberg et al. 2017
Organizational Challenges: Oligopoly, further delays very likely

Germany is currently exploring large-scale decommissioning. The work is carried out by the utilities while some works are tendered to specialized companies.

Wealer et al. (2015) suggest a potential oligopoly and the potential abuse of market power due to market concentration. Some solidification for this suggestion could have been observed in 2018: PreussenElektra awarded the dismantling of the RVI of six plants to a consortium led by waste management company GNS and Westinghouse. GNS is utilities-owned with PreussenElektra being the major shareholder with 48 percent of the shares.

Possible economies of scale with WH/GNS decommissioning six NPPs.

Only one of the 8 reactors shut down after Fukushima has been defueled: The special fuel rods of Brunsbüttel were sent to Sweden and are thought to be sold to the US.

Insufficient number of storage and transport casks for SNF, while casks for the special fuel rods are still missing.
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Key Findings in Japan

No valuable experience with decommissioning yet.

The Fukushima Accident (March 2011) caused serious trouble to the internal decommissioning funds of the operator. A strategy of Safe Storage of approx. 10 years is likely to be applied for the majority of the reactors.

Reactors can receive a unique lifetime extension of 20 years under the revised regulation (induced by the investigations of the Fukushima accident).

Full market liberalization in 2016 makes the accumulation of decommissioning funds even more difficult.

Estimated costs appear moderate and affordable but are subjected to uncertainties due to lack of experience.

For some reactors the restart option might be even more expensive than the shutdown.

<table>
<thead>
<tr>
<th>Japan</th>
<th>May 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Warm-up-stage”</td>
<td>20</td>
</tr>
<tr>
<td>of which defueled</td>
<td>1</td>
</tr>
<tr>
<td>“Hot-zone-stage”</td>
<td>0</td>
</tr>
<tr>
<td>“Ease-off-stage”</td>
<td>0</td>
</tr>
<tr>
<td>LTE</td>
<td>0</td>
</tr>
<tr>
<td>Finished</td>
<td>1</td>
</tr>
<tr>
<td>of which greenfield</td>
<td>1</td>
</tr>
<tr>
<td>Shut-down reactors</td>
<td>25</td>
</tr>
</tbody>
</table>
Organizational Challenges: Underprovisioning, Fukushima

Historically, electric utilities had to establish tangible fixed assets for the expenses of decommissioning during the period of operation through surcharges on the retail price of electricity and based on the output of a facility.

Since 3/11: total decommissioning costs are allocated by the straight-line method over the period of operation and safe storage and the surcharges were decoupled from the electricity output of a reactor.

To cover the financial shortage, many operators chose the strategy of intermediate storage (5-10 years) for their reactors in order to collect more money.

In 2015, METI estimated an average of ¥71.6 billion per reactor but more recent estimates for the five latest reactors slated for decommissioning were significantly raised to ¥160 billion (US$1.46 billion) per reactor.

Another issue for the decommissioning process in Japan is that companies are permitted to temporarily divert decommissioning funds for other business purposes and thus risking that the funds are not available when needed.
## Organizational models for decommissioning in the Case Studies

<table>
<thead>
<tr>
<th>Financing</th>
<th>Production</th>
<th>A) Public enterprise</th>
<th>B) Private enterprise (decentral or status quo)</th>
<th>C) Public tender (centralized or decentralized)</th>
<th>D) Further Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Public budget</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) External segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Internal non segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Internal segregated fund</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) Further Alternatives</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Seidel and Wealer (2016), based on Klatt (2011)
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Decommissioning is technologically and financially challenging

The country case studies also suggest that both, duration and costs have been largely underestimated. The few projects that have started encounter, in nearly all the cases, delays as well as cost increases.

Japan will enter a difficult phase in the near future—as the first reactor pressure vessel of a commercial reactor has to be removed yet.

The U.S. have decommissioned the highest number of reactors (13), but these case studies cannot be used as a reference for other cases, e.g. the removal and consequent burial of large-scale parts.

In all the cases, interim storage facilities were needed, hindering decommissioning or even rendering the regulatory release of the site impossible.

The early nuclear states UK, France, and Canada have not fully decommissioned a single reactor.

In addition, going forward, decommissioning faces a challenge in a context of low electricity prices placing a further strain on the competitiveness of nuclear power plants—and low provisions on behalf of the companies.
NPP decommissioning is outpacing new-build

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.

Until now no NPP was built under what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system.

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.

In mid-2018, a total of 115 NPPS were being decommissioned, while only 50 NPPS were being built worldwide.
Thank you for your attention!

Contact:

bw@wip.tu-berlin.de
Backup
Last but not least: the role of government for newbuild

*Today, no privately run energy conglomerate risks building a nuclear power station without government subsidies and guarantees. It is noticeable that new nuclear power stations are built particularly where the government and the energy industry form an unholy alliance.*”


<table>
<thead>
<tr>
<th>Country</th>
<th>Units</th>
<th>MWe (net)</th>
<th>Construction Start</th>
<th>Financing Type/Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>22</td>
<td>20,500</td>
<td>2009–2015</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>Russia</td>
<td>7</td>
<td>5520</td>
<td>1983–2010</td>
<td>Government</td>
</tr>
<tr>
<td>India</td>
<td>5</td>
<td>2990</td>
<td>2002–2011</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>USA</td>
<td>4</td>
<td>4468</td>
<td>1972–2013</td>
<td>Government/Private sector</td>
</tr>
<tr>
<td>UAE</td>
<td>4</td>
<td>5380</td>
<td>2012–2016</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>South Korea</td>
<td>3</td>
<td>4020</td>
<td>2008–2013</td>
<td>Government</td>
</tr>
<tr>
<td>Pakistan</td>
<td>3</td>
<td>2343</td>
<td>2011</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>Belarus</td>
<td>2</td>
<td>2218</td>
<td>2013–2014</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>Japan</td>
<td>2</td>
<td>2683</td>
<td>2007–2010</td>
<td>Government/Other</td>
</tr>
<tr>
<td>Slovakia</td>
<td>2</td>
<td>880</td>
<td>1985</td>
<td>Government/Corporate Finance</td>
</tr>
<tr>
<td>Ukraine</td>
<td>2</td>
<td>2068</td>
<td>1986–1987</td>
<td>In process</td>
</tr>
<tr>
<td>Argentina</td>
<td>1</td>
<td>25</td>
<td>2014</td>
<td>Government</td>
</tr>
<tr>
<td>Brazil</td>
<td>1</td>
<td>1245</td>
<td>2010</td>
<td>Government/Vendor</td>
</tr>
<tr>
<td>Finland</td>
<td>1</td>
<td>1600</td>
<td>2005</td>
<td>Government/corporate Finance/Project Finance (Mankala Model)</td>
</tr>
<tr>
<td>France</td>
<td>1</td>
<td>1600</td>
<td>2007</td>
<td>Corporate Finance</td>
</tr>
</tbody>
</table>

Source: IAEA-PRIS for construction data. The data on financing mechanism are from various publications, World Nuclear News, Nucleonics, Reuters, WNA country profiles, and authors’ opinion

• Hinkley Point C: contract for difference, guaranteed price of £92.50/MWh over the first 35 years
• Olkiluoto-3: fixed price contract

Source: Barkatullah and Ahmad (2017, 130).
Figure 30 | AREVA Share Price Development Since 2006

AREVA (France) Share Price Development Since 2006

*Source: Investing.com, August 2017*
Figure 34 | Toshiba Share Price Development Since 2006

Toshiba (Japan) Share Price Development Since 2006

- Share Price as of 2 January 2006: $6.15
- 25 July 2007: $9.8
- First postponement of FY16 results: 14 December 2016
- Warns of multi-billion dollar charge: 27 December 2016
- Second delay on results and control report: 15 March 2017
- Share Price as of 3 July 2017: $2.32

Source: Yahoo Finance, August 2017
Figure 35 | Kepco Share Price Development Since 2006

KEPCO (Korea) Share Price Development Since 2006

Share Price as of January 2006: $19.76
Share Price as of 3 July 2017: $17.84

Source: Yahoo Finance, August 2017
Figure 36 | CGN Share Price Development Since its Launch in 2014

CGN (China) Share Price Development Since its Launch in 2014

Percentage

- 5 June 2015
  HKD 5.43

- 19 October 2015
  HKD 3.65

- Share Price as of 10 December 2014
  HKD 3.31

- Share Price as of 3 July 2017
  HKD 2.20

Source: Yahoo Finance, August 2017
Monte-Carlo Simulation: Costs and parameters

• Fixed and variable costs of nuclear power
  • Operating costs (fixed):
    • Operation       20 €/installed kW/year
    • Maintenance     20 €/installed kW/year
    • Insurance       15 €/installed kW/year
  • Operating costs (Variable):
    • Operation       8 €/MWh_el
    • Maintenance     7 €/MWh_el

• Parameters
  • Market Variables:
    • Wholesale Electricity Base Price
    • Wholesale Electricity Peak Price
  • Power Plant Variables:
    • CO2 Price
    • Max. CO2 Price
    • Fuel Price
    • Installed Capacity (electrical)
    • Specific Investement Costs
    • Electric Efficiency
    • Load Hours

Source: Schröder et al. (2013)
# Germany: Decommissioning status I/II

## 8 commercial power reactors with running or terminated decommissioning process

<table>
<thead>
<tr>
<th>Reactor design</th>
<th>NPP</th>
<th>Shutdown</th>
<th>Reactor Model [MW]</th>
<th>Operator/Owner</th>
<th>Current Status</th>
<th>Begin of decommissioning</th>
<th>Planned termination</th>
<th>Costs [million EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR</td>
<td>Lingen</td>
<td>1977</td>
<td>1. Gen [183 MW]</td>
<td>RWE</td>
<td>LTE, 2015: license granted</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Greifswald 1-5</td>
<td>1989/90</td>
<td>4 x VVER V-230, 1 x V-213 [4 x 408 MW]</td>
<td>Energiewerke Nord GmbH</td>
<td>Stage 4</td>
<td>1995</td>
<td>-</td>
<td>6,500</td>
</tr>
</tbody>
</table>

Source: updated Wealer et al. (2015)

- Other NPPs in decommissioning process: MZFR Karlsruhe (57 MW) (Stage 4), THTR-300 (LE) (296 MW), AVR Juelich (2003, Stage 3) (13 MW), KNK II (21 MW) (1993, Stage 3)
### Germany: Decommissioning status I/II

#### 9 NPPs in post operation and Gundremmingen B (closes in 2017)

<table>
<thead>
<tr>
<th>Reactor design</th>
<th>NPP</th>
<th>Operator</th>
<th>Reactor Model [MW]</th>
<th>FE</th>
<th>SFR</th>
<th>Defuelling ends in</th>
<th>Beginn of D&amp;D</th>
<th>Estim. D&amp;D duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brunsbüttel*</td>
<td>66.6% VENE; 33.3% E.ON</td>
<td>BWR-69 [771 MW]</td>
<td>517</td>
<td>12</td>
<td>2017 (ended)</td>
<td>2017</td>
<td>10-15 years</td>
</tr>
<tr>
<td>BWR</td>
<td>Gundremmingen B</td>
<td>75% RWE; 25% E.ON</td>
<td>BWR-72 [1,284 MW]</td>
<td>3008</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Isar 1</td>
<td>E.ON</td>
<td>BWR-69 [878 MW]</td>
<td>1734</td>
<td>44</td>
<td>2018</td>
<td>2017</td>
<td>10 years</td>
</tr>
<tr>
<td></td>
<td>Krümmel</td>
<td>50% VENE; 50% E.ON</td>
<td>BWR-69 [1,346 MW]</td>
<td>1094</td>
<td>62</td>
<td>-</td>
<td>2019/2020</td>
<td>10-15 years</td>
</tr>
<tr>
<td></td>
<td>Philippsburg 1</td>
<td>98.45% EnBW</td>
<td>BWR-69 [890 MW]</td>
<td>886</td>
<td>29</td>
<td>2017</td>
<td>-</td>
<td>15 - 20 years</td>
</tr>
<tr>
<td></td>
<td>Grafenrheinfeld</td>
<td>E.ON</td>
<td>Vor-Konvoi [1,275 MW]</td>
<td>597</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Neckarwestheim 1</td>
<td>98.45% EnBW</td>
<td>2. Gen [785 MW]</td>
<td>347</td>
<td>84</td>
<td>2017</td>
<td>2017</td>
<td>15 years</td>
</tr>
<tr>
<td></td>
<td>Unterweser</td>
<td>E.ON</td>
<td>2. Gen [1,345 MW]</td>
<td>413</td>
<td>77</td>
<td>2019/2020</td>
<td>-</td>
<td>until 2025</td>
</tr>
</tbody>
</table>

Source: updated Wealer et al. (2015)

* Vattenfall awarded the contract to dismantle the RVI to Areva-EWN joint-venture in 2017
## France: Decommissioning status for EDF’s legacy fleet

<table>
<thead>
<tr>
<th>Reactor design</th>
<th>NPP</th>
<th>Reactor model [MW]</th>
<th>Operating Time</th>
<th>Current Stage</th>
<th>Initial End of Decommissioning</th>
<th>End of Decommissioning</th>
<th>Cost estimations [million EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>EL-4 (Brennilis)</td>
<td>HWGCR [70 MW]</td>
<td>1968 – 1985</td>
<td>Partial dismantling</td>
<td>2015</td>
<td>2028 (estimated)</td>
<td>458.6</td>
</tr>
</tbody>
</table>

- First GCR reactor dismantling approx. 2031-2056
- Chooz-A Stage 3 executed by Westinghouse
- cost estimates, based on contractor quotes

## Decommissioning monitoring for United Kingdom

<table>
<thead>
<tr>
<th>Reactor concept</th>
<th>Site</th>
<th>Reactor type</th>
<th>Operating time</th>
<th>Strategy</th>
<th>SLC</th>
<th>License terminates in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chapelcross</td>
<td>Magnox [4x 48 MW]</td>
<td>1959/60 -2004</td>
<td>LTE</td>
<td>Magnox Ltd</td>
<td>2128</td>
</tr>
</tbody>
</table>
The inseparable nexus: nuclear power and nuclear weapons

• Acheson-Lilienthal Report (1946, p.10): “The development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent.”

• Lovins et al. (1980, p. 1144):
  • “The propagation of nuclear power thus turns out to have embodied the illusion that we can split the atom into two roles as easily and irrevocably as into two parts—forgetting that atomic energy is a-tomic, indivisible.

• Hirschhausen (2017): interpretation of the nuclear industry in terms of “economies of scope”, where strategies, costs, and benefits must be assessed in the multiproduct context of military and civilian uses of nuclear power.
# The perspectives of nuclear power

<table>
<thead>
<tr>
<th>No Scope countries</th>
<th>Scope countries“</th>
<th>Newcomer countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany, Spain, Belgium, Italy, Switzerland, Sweden, South Korea</td>
<td>USA, UK, India, Pakistan, France, North Korea, Russia, China</td>
<td>Iran, UAE, Turkey, Saudi Arabia, Egypt, Jordan, Bangladesh, Sudan, Belarus</td>
</tr>
<tr>
<td>➔ Close down NPPs, currently no replacement foreseeable</td>
<td>➔ Scope countries call for future nuclear deployment, heavy investments into the nuclear supply chain, and retrofitting of older nuclear plants.</td>
<td>➔ High dynamics especially in the Middle East: if Iran wants reprocessing, Saudi Arabia will want it too</td>
</tr>
<tr>
<td>What about Japan, Eastern Europe?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- [Image of nuclear power plant]
- [Image of nuclear power plant]
- [Image of nuclear power plant]
Conclusion: Nuclear power is not competitive

- 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 very constraint
- Decommissioning cost of about 1000 €/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
- Until now no NPP was built under what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system
- 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)


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