Supplement of

Cross-country survey on the decommissioning of commercial nuclear reactors: status, insights, and knowledge gaps

Rebekka Bärenbold et al.

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\textsuperscript{3}: DIW Berlin, Germany
Agenda

1. Motivation and Background
2. Our Case Studies
3. Results and Insights
Nuclear decommissioning is conducted once a nuclear reactor is shut down. This includes activities from the shutdown itself, the removal of nuclear material and, depending on the target, the environmental restoration of the site. The process is lengthy and expensive. From a safety and security view, it is imperative that nuclear reactors are decom. to minimize risk. Historically, decom. has been neglected as a distant obligation. In some cases, the combination of inexperience and insufficient planning led to undesired outcomes.

Taken from Wealer & von Hirschhausen (2020) Nuclear power as a system good: Organizational models for production along the value-added chain. DIW Discussion Paper 1883. URL: http://hdl.handle.net/10419/222865.
Assuming a 40-year lifetime, many reactors built in the 1980s will begin shutting down in the coming years. All of these reactors will have to be decom. at some point. Lifetime extensions (50, 60 or 80 years) can only push this inevitability into the future. The global decom. industry is still developing and remains largely untested as only around a dozen commercial reactors have been fully decommissioned.
Nuclear Decommissioning
Strategies and Technical Approach

**Direct Dismantling**
- Decom. is conducted directly after shutdown of the NPP
- Institutional knowledge of on-site personnel can be utilized
- Faster release of site for other use
- Most often used strategy

**Deferred Dismantling**
- After shutdown, the NPP is placed into "longterm enclosure" for years to decades
- This reduces hazards through radiation as radioisotopes decay

**Entombment**
- Remaining radioactive material is permanently encapsulated on site
- Typically, this strategy is an appropriate strategy after an accident

**Warm-Up Stage**
- Includes post-operational phase and preparatory tasks
- Reactor core is defueled and first components are removed

**Hot-Zone Stage**
- Highly contaminated parts (e.g., reactor pressure vessel) are removed
- It is the most dangerous, complex and costly part of the process

**Ease-Off Stage**
- Buildings and remaining components are decontaminated and demolished
- Depending on the target (greenfield vs. brownfield), the landscape may be remediated
Our Research

• We explore the current situation in **six countries**: France, Germany, USA, UK, Switzerland and Sweden

• We want to understand what the existing **institutional, regulatory** and legal, **financial**, and **technical regimes** for decommissioning in these countries are

• We identify **insights** from comparing the countries’ approaches in order to **identify research gaps**

• In our ongoing project, we subsequentially aim at answering some of these gaps

• Others can be picked up by future research
Agenda

1 Motivation and Background
2 Our Case Studies
3 Results and Insights
### Case Study Overview

#### General Information

**France**
- 56 (somewhat) homogeneous NPPs operational that account for 2/3 of electricity generation
- New build ongoing at Flammanville
- Single utility responsible (EDF)

**Germany**
- Since April 2023, end of commercial operation of nuclear power reactors
- Parallel decommissioning ongoing at over 30 reactors
- Diverse ownership structure, special case for GDR legacy fleet

**Sweden**
- 30% of Swedish electricity generated by 13 nuclear reactors
- Legal pathway for new reactor construction paved in 2022

**Switzerland**
- 4 operational NPPs generate 1/3 of Swiss electricity
- End of commercial operation planned for 2040s
- Prohibition on nuclear new builds by law since 2017

**United Kingdom**
- 10 reactors account for 15% of British electricity generation
- Fleet consists of mainly gas-cooled reactors, so-called “legacy” fleet of Magnox reactors challenging
- New build ongoing (Hinkley Point C)

**United States**
- Largest commercial power reactor fleet worldwide (92 operating)
- Significant support schemes for nuclear power in place
- New build at Vogtle Station delayed and expensive
## Case Study Overview
Decommissioning progress as of June 2022

<table>
<thead>
<tr>
<th>Country</th>
<th>Closed reactors (total)</th>
<th>Warm-Up</th>
<th>Hot-Zone</th>
<th>Ease-Off</th>
<th>LTE</th>
<th>Radiologically Decommissioned (of which are Greenfield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>14</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>8</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Germany</td>
<td>30</td>
<td>9</td>
<td>8</td>
<td>9</td>
<td>1</td>
<td>4 (3)</td>
</tr>
<tr>
<td>Sweden</td>
<td>7</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 (0)</td>
</tr>
<tr>
<td>UK</td>
<td>34</td>
<td>13</td>
<td>9</td>
<td>0</td>
<td>8</td>
<td>0 (0)</td>
</tr>
<tr>
<td>USA</td>
<td>41</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>13</td>
<td>17 (6)</td>
</tr>
</tbody>
</table>

Of our case study countries, only Germany and the USA have completed decommissioning at some reactors. Most projects have been ongoing for years (or work has not yet begun).
Agenda

1. Motivation and Background
2. Our Case Studies
3. Results and Insights
Insights and Research Gaps
Overview

- Organization / Regulation
- Financing
- Production
- Waste Management
## Insights and Research Gaps

**Organization of Ownership as of October 2022**

<table>
<thead>
<tr>
<th>CENTRALIZED</th>
<th>PUBLICLY OWNED</th>
<th>INVESTOR OWNED</th>
<th>COOPERATIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOVERNMENT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DECENTRALIZED</td>
<td>United Kingdom</td>
<td>United States</td>
<td></td>
</tr>
</tbody>
</table>

- **Centralized**
  - France
  - United Kingdom

- **Decentralized**
  - United States
  - Germany
  - Switzerland
  - Sweden

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Bärenbold, Bah, Lordan-Perret, Weigt (University of Basel) and Steigerwald, von Hirschhausen, Wealer, Wimmers (TU Berlin)

Decommissioning of Nuclear Reactors: Status, Insights and Knowledge Gaps | safeND | 14th September 2023
### Organization / Regulation

<table>
<thead>
<tr>
<th>Interlinkage between ownership and nuclear decom.</th>
<th>Influence of regulatory framework on nuclear decom.</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Direct influence of ownership on decommissioning via financing, scheduling, production of decom. work and liability for unfunded work.</td>
<td>• Decommissioning process highly dependent on country-specific laws and regulations.</td>
</tr>
<tr>
<td>• Possible differences of incentivation for swift, safe and cost-efficient decommissioning for private owners vs. government owners.</td>
<td>• These differ amongst countries, e.g., in terms of responsible agencies (several vs. a single agency).</td>
</tr>
<tr>
<td></td>
<td>• Key challenge for “newcomer” countries is to harmonize domestic with foreign regulations.</td>
</tr>
</tbody>
</table>
## Insights and Research Gaps

### Financing of Nuclear Decommissioning

<table>
<thead>
<tr>
<th>State Funded</th>
<th>Public Budget</th>
<th>Internal Segregated</th>
<th>Internal Non-Segregated</th>
<th>External Segregated</th>
<th>Guarantees</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>Germany</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>France</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>United Kingdom</td>
<td></td>
<td></td>
<td>Sweden</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>Sweden</td>
<td>United States</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **United Kingdom**: State Funded, Public Budget, Guarantee
- **Germany**: State Funded, Public Budget, Internal Segregated, Internal Non-Segregated, External Segregated
- **France**: State Funded, Internal Segregated
- **United States**: State Funded, External Segregated
- **Switzerland**: State Funded, Polluter Pays
- **Sweden**: Polluter Pays, Guarantees
## Insights and Research Gaps

### Financing

<table>
<thead>
<tr>
<th>Improving of cost and contingency estimations</th>
<th>Decommissioning fund adequacy and transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cost estimations vary significantly; historically <strong>costs</strong> have been underestimated</td>
<td>• Decommissioning fund volumes are not always publicly accessible and it often remains unclear for what money is used</td>
</tr>
<tr>
<td>• <strong>Accurate estimations</strong> might help reduce liability risks and understand incentivation of actors</td>
<td>• <strong>Transparency and increased fund scrutiny</strong> might reduce liability risks</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Determining financial liability</th>
<th>External influences on decommissioning funds</th>
</tr>
</thead>
<tbody>
<tr>
<td>• In some countries (esp. US), final <strong>financial liability is sometimes unclear</strong></td>
<td>• Market development can influence decommissioning funds that are often accumulated over NPP lifetime</td>
</tr>
<tr>
<td>• Understanding how other countries might account for fund shortfalls could increase responsibility for cost-efficient decom.</td>
<td>• <strong>Identifying influences and potential risks</strong> for these funds could increase <strong>fund resilience</strong></td>
</tr>
</tbody>
</table>
Insights and Research Gaps
Production of Nuclear Decommissioning

MAKE

- French PWR fleet
- UK PWR
- Former GDR Legacy Fleet

HYBRID

- French “special” fleet
- UK Legacy + AGR fleets
- West German NPPs

BUY

- Switzerland
- Sweden
- United States
Insights and Research Gaps

Production

The make or buy decom. production decision

- Nuclear reactors are highly asset specific, resulting in limited number of actors active in the market
- No country follows a single approach
- External or internal conditions must exist that influence decisions

The role and influence of specialized firms

- Highly specialized actors are emerging in the decom. market
- These specialists have begun to take over whole to-be-decommissioned plants or are responsible for full reactor fleets
- Possible efficiency increases through specialization might occur

Developing the decommissioning supply chain

- With many NPPs likely to be coming offline at similar times, concerns regarding possible supply chain bottle necks are emerging (human capital, specialized material & infrastructure)

Inspecting claims of efficiency

- Parallel decommissioning of (somewhat) homogeneous reactor fleets are proposed to go hand in hand with efficiency gains
- Past experience (esp. in nuclear construction) shows that such claims were historically unfounded
Insights and Research Gaps

Waste Management

- There are different types of radioactive waste which are disposed of in different types of facilities
- Almost all countries struggle with the management of High-Level Waste (HLW) and Spent Nuclear Fuel (SNF)
- Switzerland, Sweden and France have chosen a site for a deep geological repository to store HLW/ SNF
- Five countries (all except for France) have currently an interim storage facility for HLW/ SNF available
- Low-Level Waste (LLW) is the majority of waste arising from nuclear decommissioning
- Thus, access to LLW facilities might become a critical chokepoint for decommissioning
- Our surveyed countries all have dedicated nuclear waste regulations
- Variation exists in the involvement of the government
Insights and Research Gaps
Waste Management

Waste Management

Access to waste disposal facilities

- Worldwide, **no final geological repository for highly radioactive waste is in operation**
- Three of our six countries have identified a location
- **Access to disposal routes** for low, medium and high-level waste is imperative for nuclear decommissioning to succeed
- Currently, most waste is stored in **interim facilities** that might be in operation for many decades
- **Lack of disposal routes** probably increases decommissioning duration and cost
Conclusion

• Our survey paper brings together insights from six country case studies on decommissioning commercial NPPs

• We focused on organization/ regulation, financing, production and waste management

• The results from our survey shows that there are many differences between the countries, yet similarities arise

• Ultimately, our overarching goal is to find and evaluate best practices in the nuclear decommissioning industry

• Our insights here will help us on this path
This research is freely accessible

**DIW Data Documentation 104**: Decommissioning of Nuclear Power Plants: Regulation, Financing, and Production

https://dx.doi.org/10.18723/diw_ddc:2023-104


https://edoc.unibas.ch/93620/1/20230213094735_63e9f9279b5a5.pdf
Thank you for your attention!

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## Generalized Regulation

<table>
<thead>
<tr>
<th>Operation</th>
<th>Warm-Up Stage</th>
<th>Hot-Zone Stage</th>
<th>Ease-Off Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
<td>Phase 3</td>
</tr>
<tr>
<td></td>
<td>Post shutdown transition</td>
<td>Radiological decommissioning</td>
<td>Site restoration</td>
</tr>
</tbody>
</table>

### Regulatory requirement

- **Brownfield**: Released for restricted use
- **Greenfield**: Released for unrestricted use

**Idiosyncratic regulatory oversight**

**Allowed decommissioning timeframe: up to 100 years!**