TECHNISCHE UNIVERSITÄT BERLIN

18th IAEE European Conference, Milan
25 July 2023

Lessons for the Organization of Nuclear Decommissioning from the UK and the US: Risks, Challenges, and Opportunities

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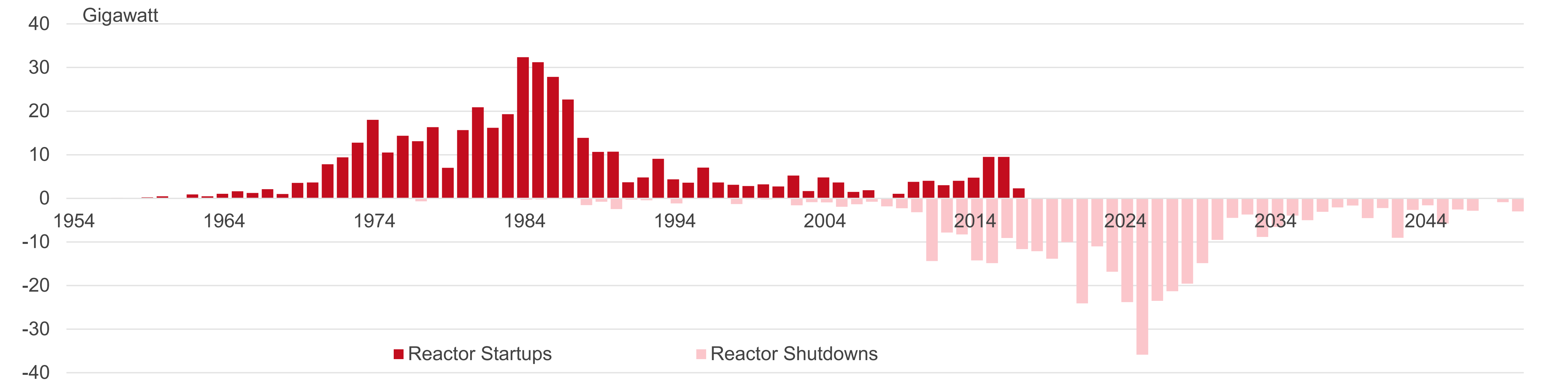
Nuclear Decommissioning
Relevance of Nuclear Decommissioning

- 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 decommissioned at some point
- Lifetime extensions (50, 60 or 80 years) can only push this inevitability into the future

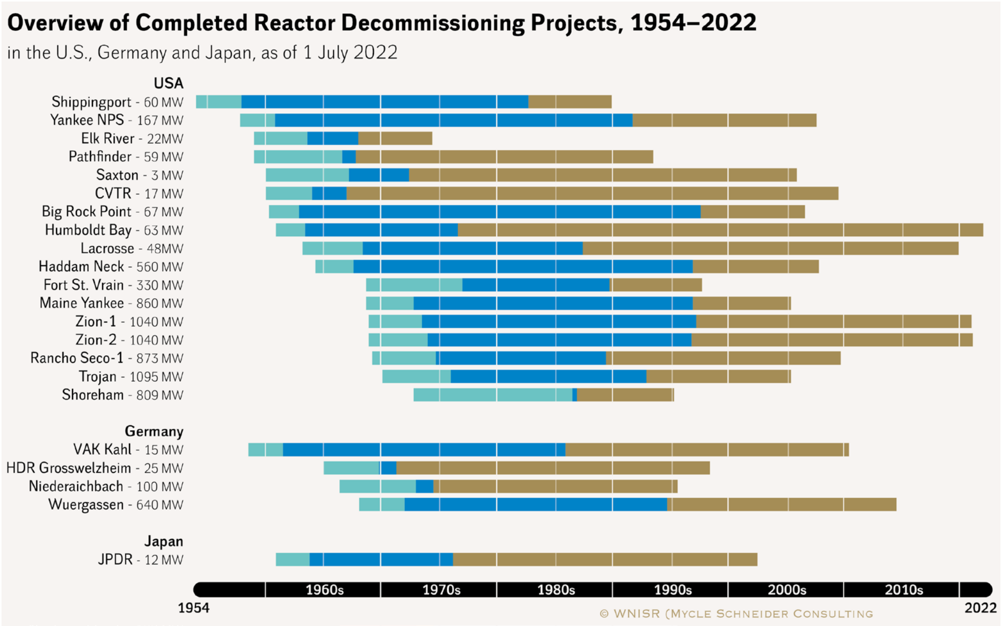
Distribution of Global Nuclear Reactor Startups and Shutdowns

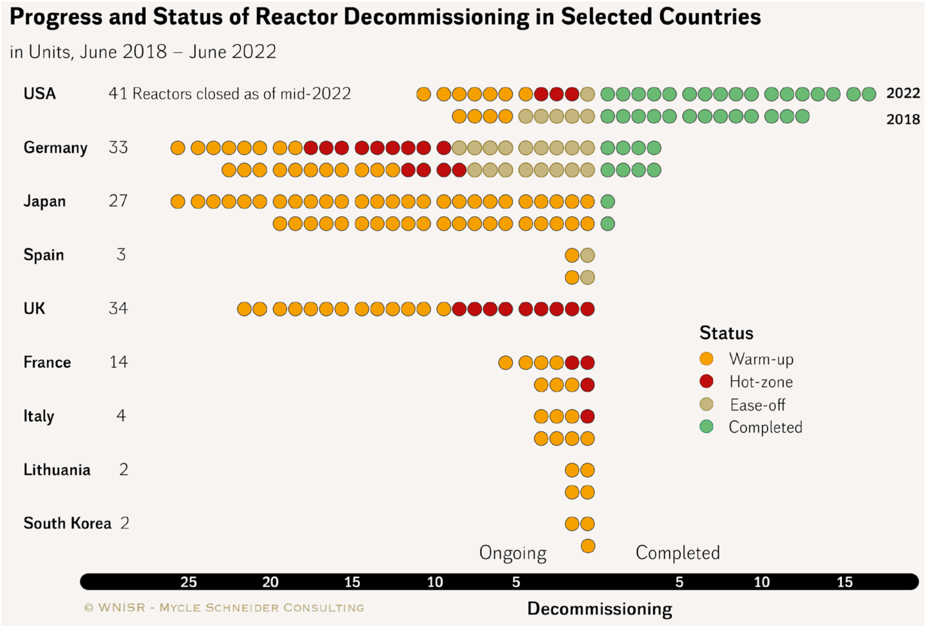


Taken from Wealer et al. (2018).

Nuclear Decommissioning
Status of Nuclear Decommissioning Projects Worldwide

As of June 2022, 204 nuclear reactors were closed world-wide. Of these, only 22 reactors have been fully decommissioned. 120 are undergoing some form of active decommissioning, while 52 are in so-called "longterm enclosure".

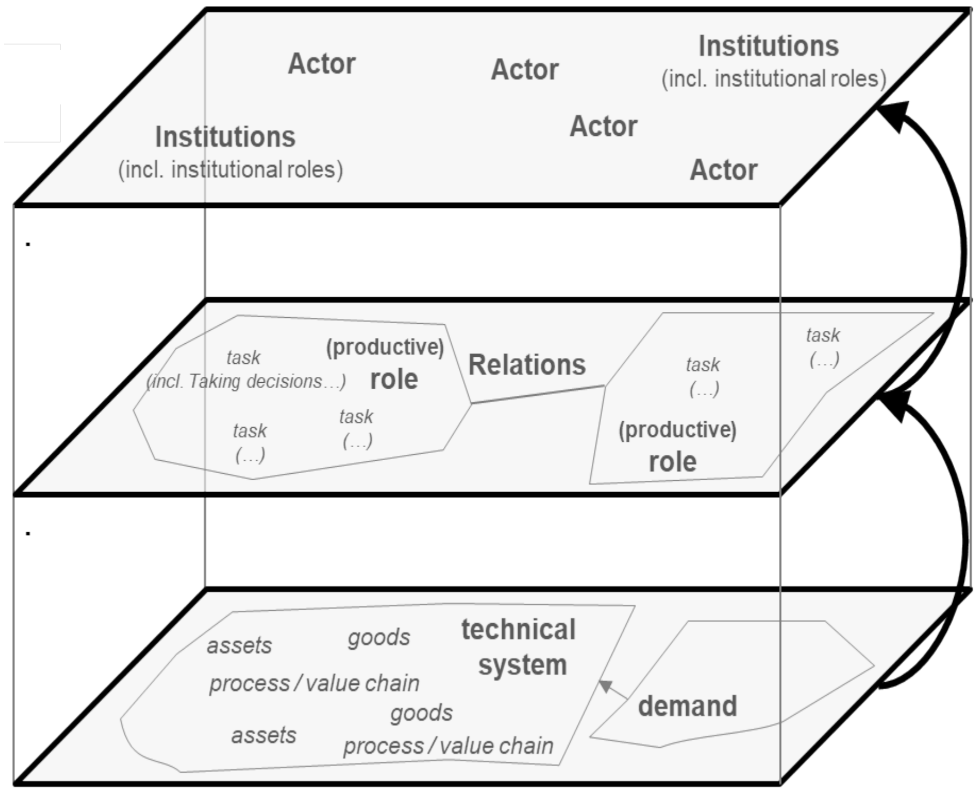




The **nuclear industry** is **inexperienced** in decommissioning – and regulation differs amongst various countries. As the relevance of decommissioning will only increase in the future, we ask whether **"best practice" organizational models** can be identified?

Taken from Schneider et al. (2022)

System Good Analysis
Methodological Framework by Beckers et al. (2012)



Source: Beckers et al. (2012)

- The framework was developed for the implementation or the supply of so-called “system goods”.
- A system good is a complex good or service, that often includes the supply of a variety of services, which must be produced upstream or offered in parallel.
- This complex web of goods and services involves a variety of actors, which results in the need for coordination between these actors.
- The framework was developed by the team around Prof. Beckers of the TU Berlin in the stream of new institutional economics.

System Good Nuclear Decommissioning
Technical System

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

Decommissioning Strategies	3-Stage-Classification
Immediate Dismantling: Decommissioning is conducted immediately after shutdown	**Warm-up-Stage**: Preparational steps for the hot-zone stage, reactor is defueled
Deferred Dismantling: Reactor is placed into long-term enclosure (LTE) to allow for radiation levels to decline. Decommissioning begins several years to decades after shutdown.	**Hot-zone-Stage**: Removal of reactor pressure vessel & internals and biological shield
Entombment: Reactor is enclosed in safe material (e.g., concrete) for an indefinite period. Method of last resort that was used at Chernobyl.	**Ease-off-Stage**: Removal of operating systems and decontamination of buildings

Sources: Wimmers et al. (2023), IAEA (205), Irrek (2019), Park et al. (2022)

System Good Nuclear Decommissioning
Processes and Assets

Nuclear decommissioning consists of many **interdependent**, highly **complex processes** that, depending on the stage, require certain assets.

Decommissioning is characterized by **high uncertainty** (e.g., unknown contamination of buildings) and **asset specificity** (e.g., use of specialized tools and diverse nuclear fleets).

Increased **frequency** of transactions is envisioned by the industry but remains **questionable** (e.g., can tools be safely reused?)

Exemplary processes and assets:

Warm Up Stage	Hot Zone Stage	Ease Off Stage
• Processes • Defueling of reactor core and spent fuel pools • Dismantling of first redundant systems • Assets • Transport and storage casks • Decontamination tools	• Processes • Dismantling of reactor pressure vessel and internals • Dismantling of cooling circuit • Assets • Highly specific tools for dismantling (e.g., underwater manipulators)	• Processes • Removal of operating systems • Demolition and decontamination of buildings • Assets • Transport and storage casks • Disposal facility (or access to)

Sources: Wimmers et al. (2023), Weinand (2022), Suh et al. (2018), Borchardt (2019), Wealer and von Hirschhausen (2020)

System Good Nuclear Decommissioning
Tasks, Roles, Actors (Production)

“a firm [has] […] a role to play in the economic system if it [is] possible for a transaction to be organized within the firm at less cost than would be incurred if the same transaction were carried out through the market” – Coase (1988, 19)

In general, two approaches to the organization of nuclear decommissioning exist (Cacuci 2010).

Vertically Integrated (“MAKE”)

Owner / Operator → NPP

Conducts decommissioning on own behalf with own staff (“in-house”)

Examples: France, Ex-GDR NPPs

Hybrid

Owner / Operator ⇢ NPP

Third-Party Decom. Contractors ⇢ NPP

Tasks are conducted in-house or by third-party contractors

Examples: West German NPPs, Switzerland, Sweden,…

Market Based (“BUY”)

Owner / Operator → NPP

Third-Party Decom. Contractors → NPP

License remains with operator or can be transferred

Conducts individual tasks or turn-key project

Examples: US, UK PBO,

Sources: Wimmers (2023)

System Good Nuclear Decommissioning

Tasks, Roles, Actors (Financing)

Public Budget

- Funds come from the government's budget
- Can sometimes go against "polluter-pays-principle"
- Examples: GDR decommissioning and UK legacy and AGR fleets

Internal Segregated

- Nuclear plant licensees make payments to a fund which self-administered and -managed
- These funds are separated from other business interests and as ear-marked
- Example: France

Internal Non-Segregated

- Funds are self-administered but need not necessarily be separated from other company business interests or assets
- Concerns about liquidity and sufficiency have been raised
- Examples: West German NPPs

External Segregated

- Nuclear plant licensees make regular payments to an externally managed fund (or funds) that are completely separated from other assets
- Once this money is deposited, control over its use is lost
- Example: Switzerland (STENFO)

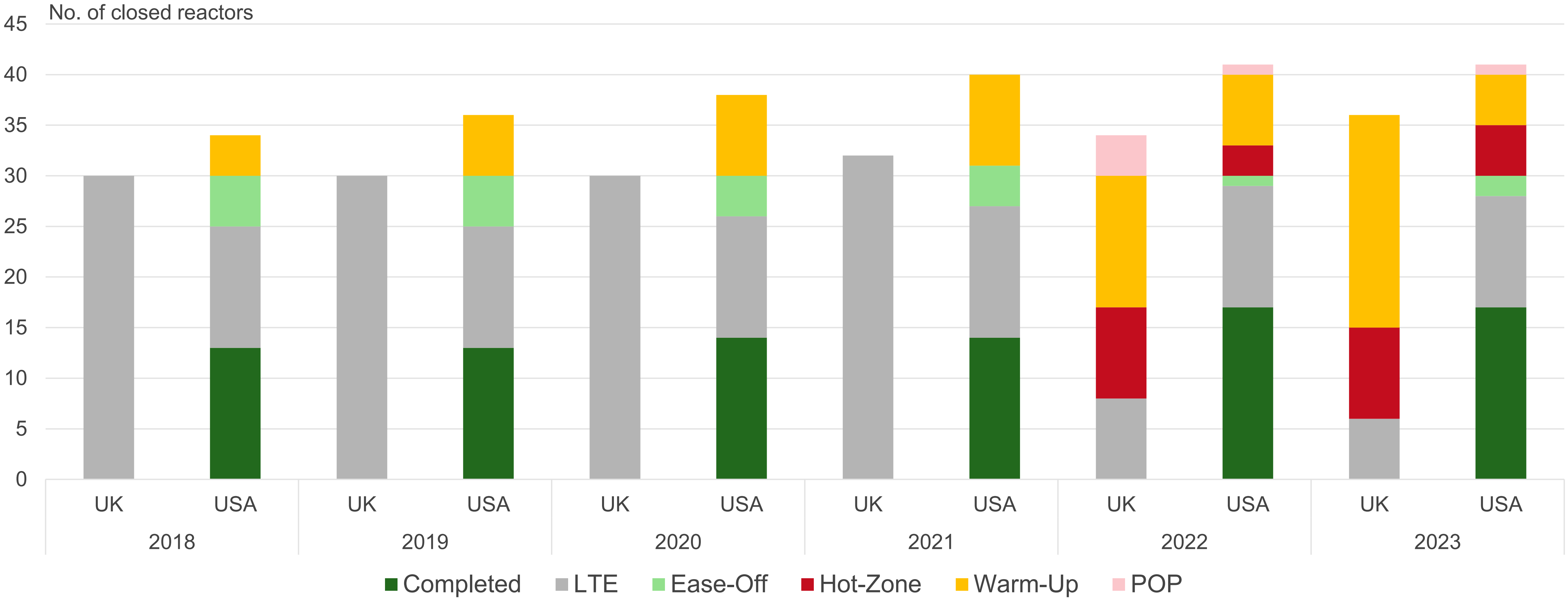
Surety Methods (Guarantees)

- In the USA, licenses may use a several financial instruments (or a combination) including surety bonds, letters of credit, parent company guarantees, …
- 30% of licensees use this approach, alone or in combination

Sources: Wealer, Seidel, and von Hirschhausen 2019; Moriarty 2021; STENFO 2020; Schneider et al. 2018; OECD/NEA 2006; 2016; Irrek 2019, Lordan-Perret et al. (2021)

Nuclear Decommissioning in the United Kingdom & United States

Progress over the last few years



POP = Post-operational phase (short-term phase directly after shutdown before decommissioning begins, i.e. due to lack of licenses)
Sources: Schneider et al. (2018, 2019, 2020, 2021, 2022), For 2023: Own compliation of various sources.

Nuclear Decommissioning in the United Kingdom

Timelines

MAKE

Pre-1990
Responsibility with CEGM that operated all commercial NPPs in the UK

1990-1996
Nuclear Electric plc operating PWRs and AGRs responsible for decommissioning

1996-2004
Waste disposal and decommissioning responsibilities with Magnox Electric plc for legacy fleet

1996-2009
British Energy formally responsible for AGR and PWR decomissioning; NLF created for financing

Post-2009
Defueling of AGRs to be conducted by EDF Energy, then transfer to NDA responsibility

Post-2009
Decommissioning of PWRs to be fully conducted by EDF Energy

Post-2021
All responsibilities for legacy fleet lie with NDA

HYBRID

2004-2021
PBO scheme active for Magnox Ltd, DSRL Ltd, LWLR Ltd, and Sellafield Ltd; NDA created

t_{-3} t_{-2} t_{-1} t_0

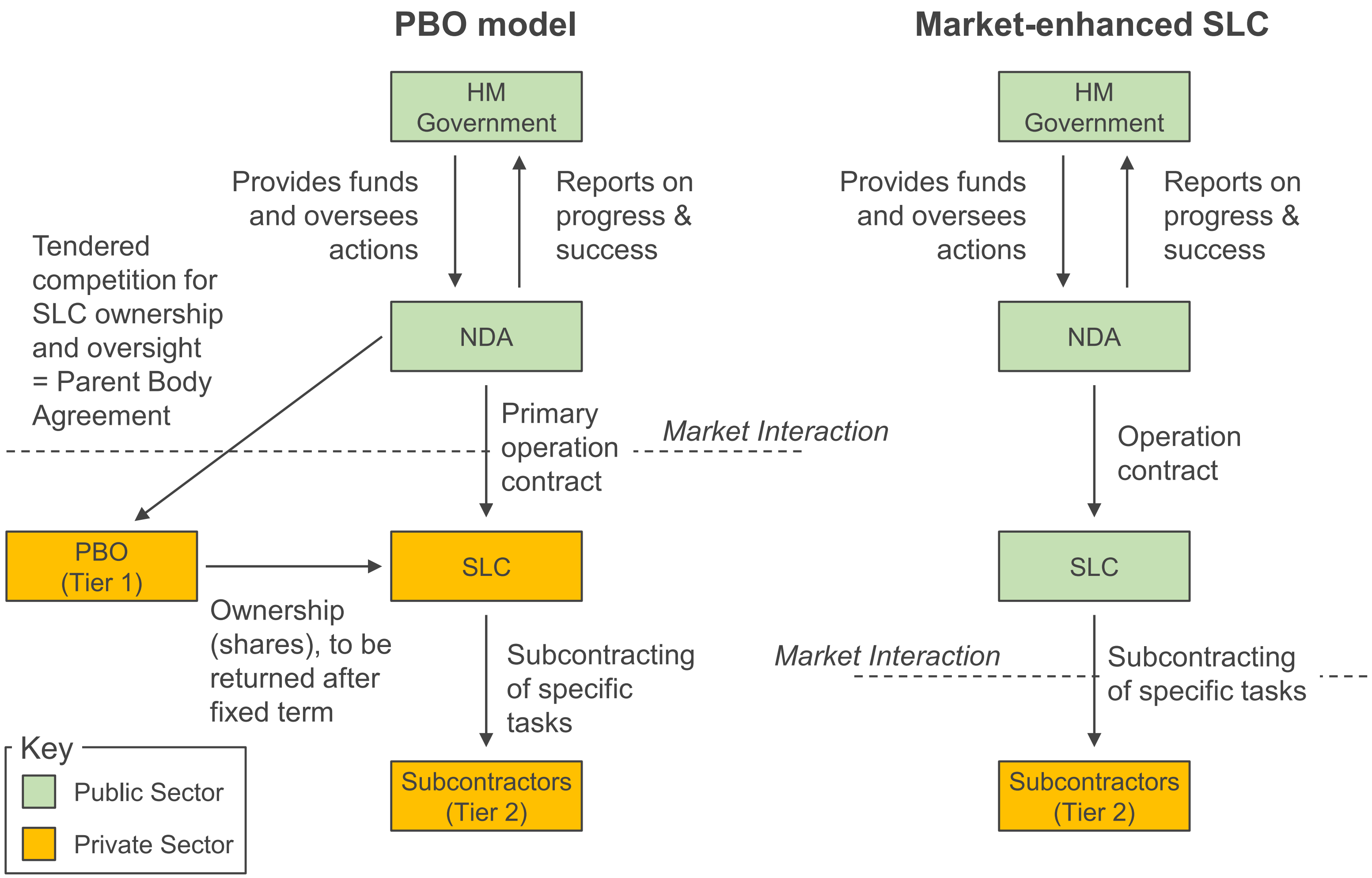
Financing Options in the UK

- Public Budget
- External Segregated
- Internal Segregated

CEGM = Central Electricity Generating Board; NPP = Nuclear Power Plant; PWR = Pressurized Water Reactor; AGR = Advanced Gas-Cooled Reactor; NLF = Nuclear Liabilities Fund; NDA = Nuclear Decommissioning Authority; PBO = Parent Body Organization

Sources: Rhodes et al. (2014), Hood (1995), Foster et al. (2021), Wimmers et al. (2023), MacKerron (2015), Lal (2013), Haraldsen (2018), Holliday (2021), NDA (2021), House Of Commons (2020) and others.

Nuclear Decommissioning in the United Kingdom
Parent-Body-Organization



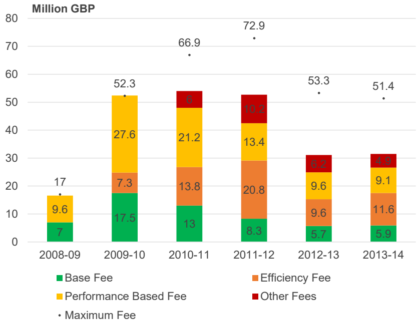
- From 2004 onwards, the UK introduced the "Parent-Body-Organization" (PBO) model to nuclear decommissioning
- The goal was to introduce competition to nuclear decommissioning while keeping (financial) liabilities for decommissioning and waste management with the state
- After initial efficiency gains, the scheme was retracted in steps for all nuclear assets as inefficiencies became apparent
- Today, the UK's decommissioning industry is fully vertically integrated

Sources: MacKerron (2012), NDA (2014)

Nuclear Decommissioning in the United Kingdom
Reasons for PBO Failure

Information Asymmetry

- PBOs were able to exploit lack of knowledge/oversight of NDA
- Opportunistic behavior resulted in focus on short-term efficiency gains to earn fees, but long-term investments were not made (e.g., Sellafield)



Complexity and Uncertainty

- Nuclear decommissioning was considered with less priority in the UK until the early 2000s
- By then, information on waste had been lost or radioactive waste sludge had formed
- Early GCRs are complex to decommission due to underground structures and contamination from radioactive gas

Transaction Costs

- Reimbursable contracts were replaced by Target-cost based contracts that required extensive monitoring to set the base-line; complicated by information asymmetry between NDA and (former) PBOs
- Monitoring of progress for fee payments highly complex
- Tendering highly complex and evaluation of bids difficult

Asset Specificity

- UK legacy fleet is highly diverse, various reactor types, models and designs; an initially adopted blanket strategy was abandoned and now site-specific approaches are tested
- Sellafield is the most complex site in the UK (and possibly Europe) which required individualized approaches

Nuclear Decommissioning in the United Kingdom
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Decommissioning of PWRs to be fully conducted by EDF Energy

Post-2021
All responsibilities for legacy fleet lie with NDA (final target 2120s…)

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t_{-3} t_{-2} t_{-1} t_0

Financing Options in the UK
Public Budget | External Segregated | Internal Segregated

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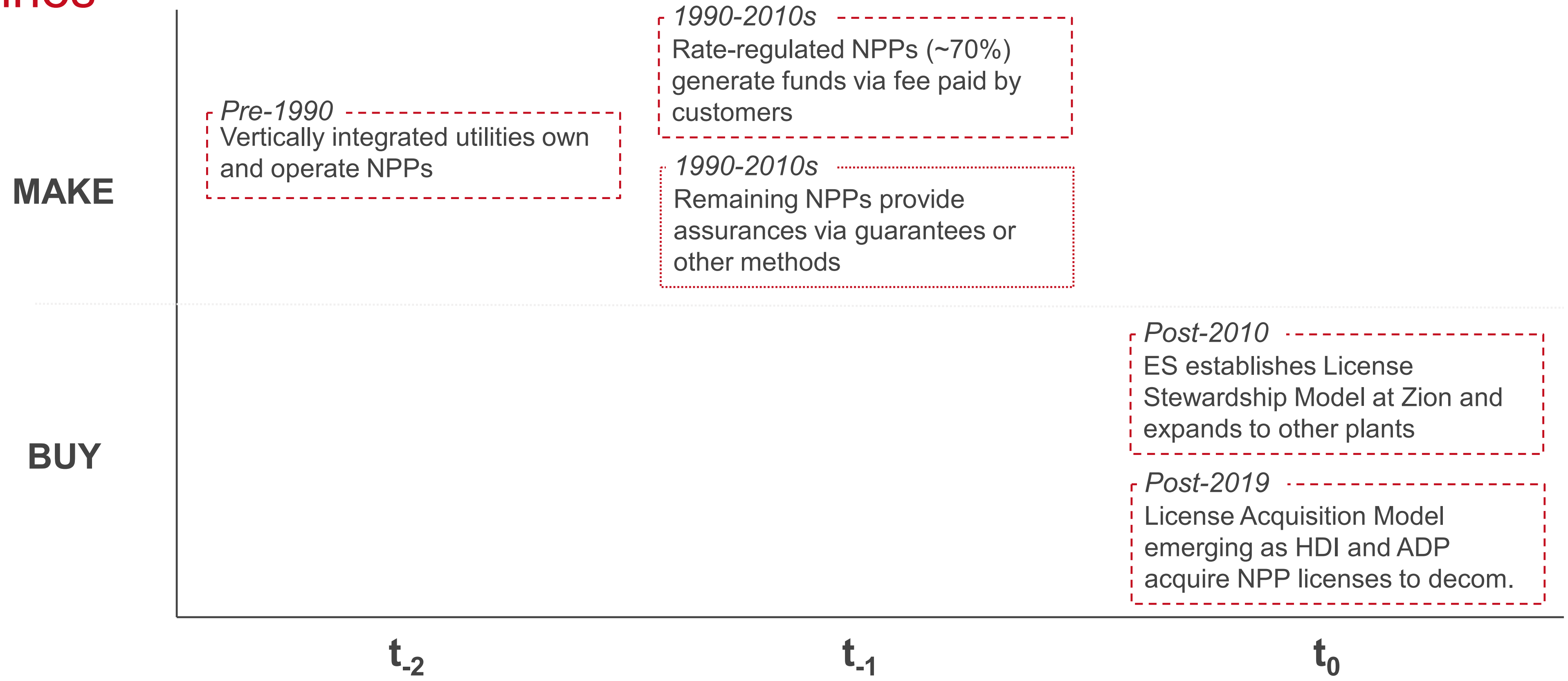
Nuclear Decommissioning in the United States
Timelines



Financing Options in the US

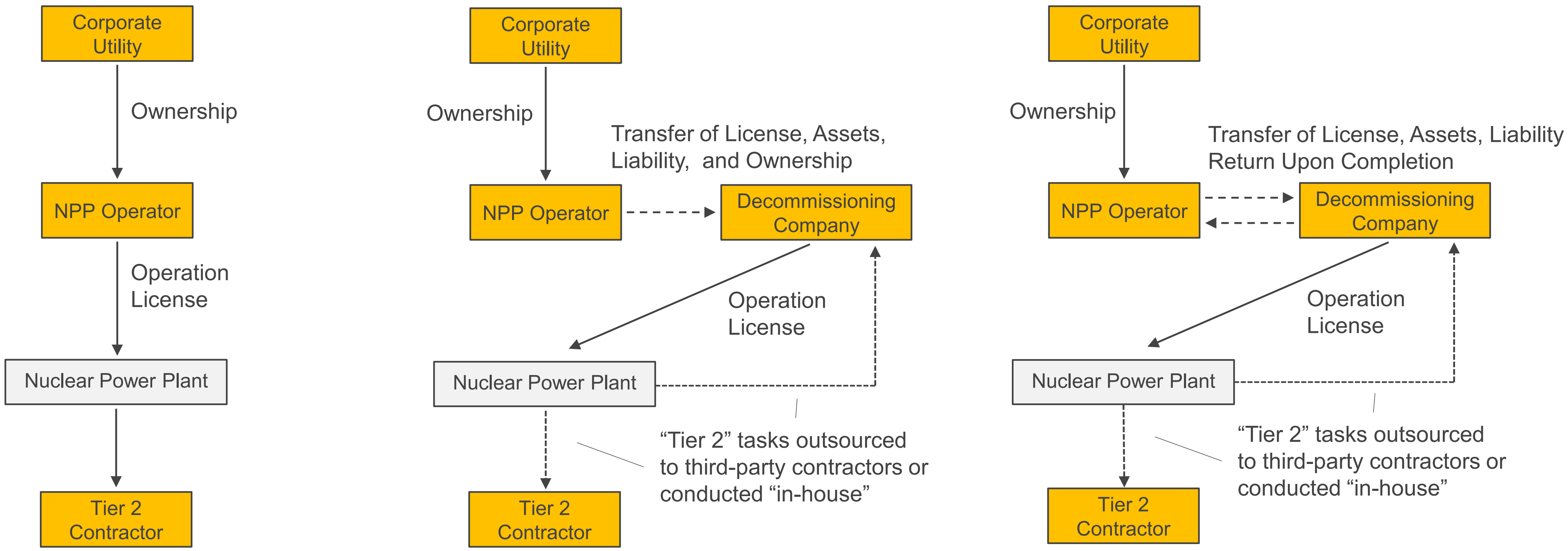
External Segregated | Surety Methods

NPP = Nuclear Power Plant; ES = Energy Solutions; HDI = Holtec Decommissioning International; ADP = Accelerated Decommissioning Partners

Sources: Lordan-Perret et al. (2021), Borenstein and Bushnell (2015), Davis and Wolfram (2012), Bah (2023), Stenger et al. (2019), Schneider et al. (2018), and others.

Nuclear Decommissioning in the United States
Two “new” organizational models have emerged

Operation and Conventional Decommissioning | License Acquisition | License Stewardship



Nuclear Decommissioning in the United States
License Stewardship and Acquisition Case Studies

License Stewardship

- Energy*Solutions* has international experience in nuclear decommissioning (former PBO in UK!)
- Leverages extensive asset base for decommissioning (low-level waste, waste processing, transportation, logistics)
- Completed decommissioning of Zion 1-2 and LaCrosse. Ongoing work at TMI-2 and Kewaunee
- Decommissioning of Zion completed within 13 years (2007-2020)
- Possibly Incentivized by access to Decommissioning Trust Fund and provision of waste removal route

License Acquisition

- All-inclusive fuel management contracts across U.S. and globally (wet and dry storage, ISFSI construction, spent fuel loading services)
- Supplier of NRC licensed dry cask storage
- Decommissioning subsidiary (HDI) currently overseeing decom at four NPPs (latest Palisades*)
- Ongoing plans for consolidated interim waste storage facility in New Mexico ~ legal challenges
- However, unclear on the financial motivation as (officially) excess cash in DTFs must be returned to rate payers (except for Indian Point)

*Palisades might be restarted, ongoing discussions with regulators and state government.

Nuclear Decommissioning in the United States
Possible benefits?

Information Asymmetry

- With license stewardship, information asymmetry remains, as the original licensee might face opportunistic behavior by steward
- With license acquisition however, information asymmetry risks are eliminated as responsibility is transferred to new licensee (shirking risk reduced!)

Complexity and Uncertainty

- By directly decommissioning NPPs and directly employing former operational staff, uncertainty is reduced on-site
- However, risks remain that highly complex sites will not be decommissioned by profit-maximizing decommissioning firms as DTF funds might not suffice

Transaction Costs

- Transaction costs are reduced significantly through the turn-key approach and unlimited contracts -> monitoring costs are reduced for the original licensee
- Costs of discovery remain (DTF + physical state of site)
- Several license transfers might however increase need for regulatory oversight and scrutiny as profit-maximizing firms might attempt at "cutting corners"

Asset Specificity

- The US fleet is somewhat homogeneous (mostly LWRs, of which 2/3 PWR); models and generations still vary and pose uncertainties
- Also the ownership structure is highly diverse
- Deregulated and regulated markets could hinder model implementation

Nuclear Decommissioning in the United States
Chances and Risks for International Decommissioning Industry

These models can only function in the US because some necessary conditions are met (Stenger et al. (2019)):

- Flexible license transfer mechanisms
- Plant-specific nuclear decommissioning trust funds
- (financial) waste management responsibilities pooled with the US federal government

Chances	Risks
• Faster decommissioning reduces safety and security risks and possible reduces cost and sites can be reused for other (industrial) purposes • Efficiency gains and learning might benefit future decommissioning projects as standardization and new technologies are implemented and might be implemented elsewhere! • Clearly defined waste management pathways	• Profit-maximizing actors might cut corners in terms of security and safety • Plants with limited DTF funds, high uncertainty or asset specifity might not be viable for model and might have to be “cleaned up” by final liability holder, which could be the state (or other actor) • secure interim waste storage pathways limit the necessity to provide final solution

Conclusion

Nuclear decommissioning is highly complex, asset specific and underlies severe uncertainty.
This limits the widespread implementation of “universal” organizational models in different countries and results in the emergence of individual designs. **But can these be applied to other countries?**

The UK’s PBO model failed due to bad governance and lack of oversight and the high transaction costs resulting from the legacy fleet’s complexity and underlying uncertainty. Returning to a more vertically integrated approach might increase efficiency for this case.

In the US, “new” organizational models might result in increased efficiency for some more standardized reactor fleets, while others could fall behind.

Preconditions for these models to function are flexible license transfer mechanisms, plant-specific financing, (somewhat) resolved waste management responsibilities, a capable nuclear decommissioning industry, and others (subject to future research).

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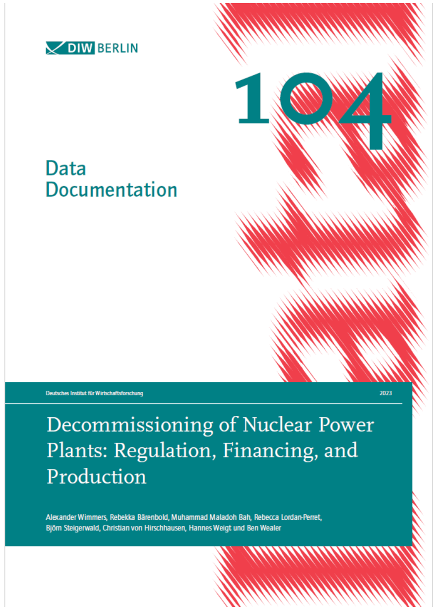
Background research is freely accessible

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



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

IAEE Webinar: Decommissioning of Nuclear Power Plants: A New Challenge of Energy Economics

https://www.iaee.org/en/webinars/webinar_cvh.aspx

https://www.youtube.com/watch?v=xZPUqKgAScs

This research is funded by Swiss National Science Foundation (SNSF) and the Deutsche Forschungsgemeinschaft (DFG), grant number 100018L 185154.

Thank you for your attention!

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Technical Process
Three-Stage Classification

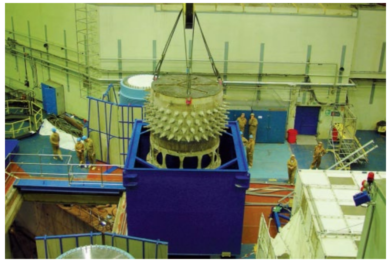
BACK-UP

Warm-Up-Stage

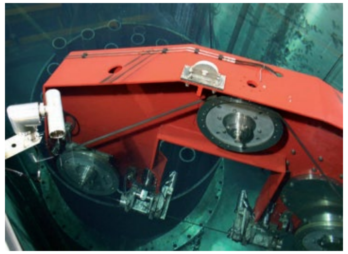
- Removal of spent fuel ("Defueling")
- Overview of contaminated inventory
- Removal of all machines and components that are not needed for hot-zone dismantling
- Set-up of technical and logistical infrastructure for hot-zone tasks
- Dismantling of contaminated machinery, such as steam generator
- Preparation of dismantling of strongly contaminated components and machinery

Hot-Zone-Stage

- Dismantling of stronlgy contaminated machinery and components, such as reactor pressure vessel or biological shield



Remote underwater cutting



„One piece" dismantling

Ease-Off-Stage

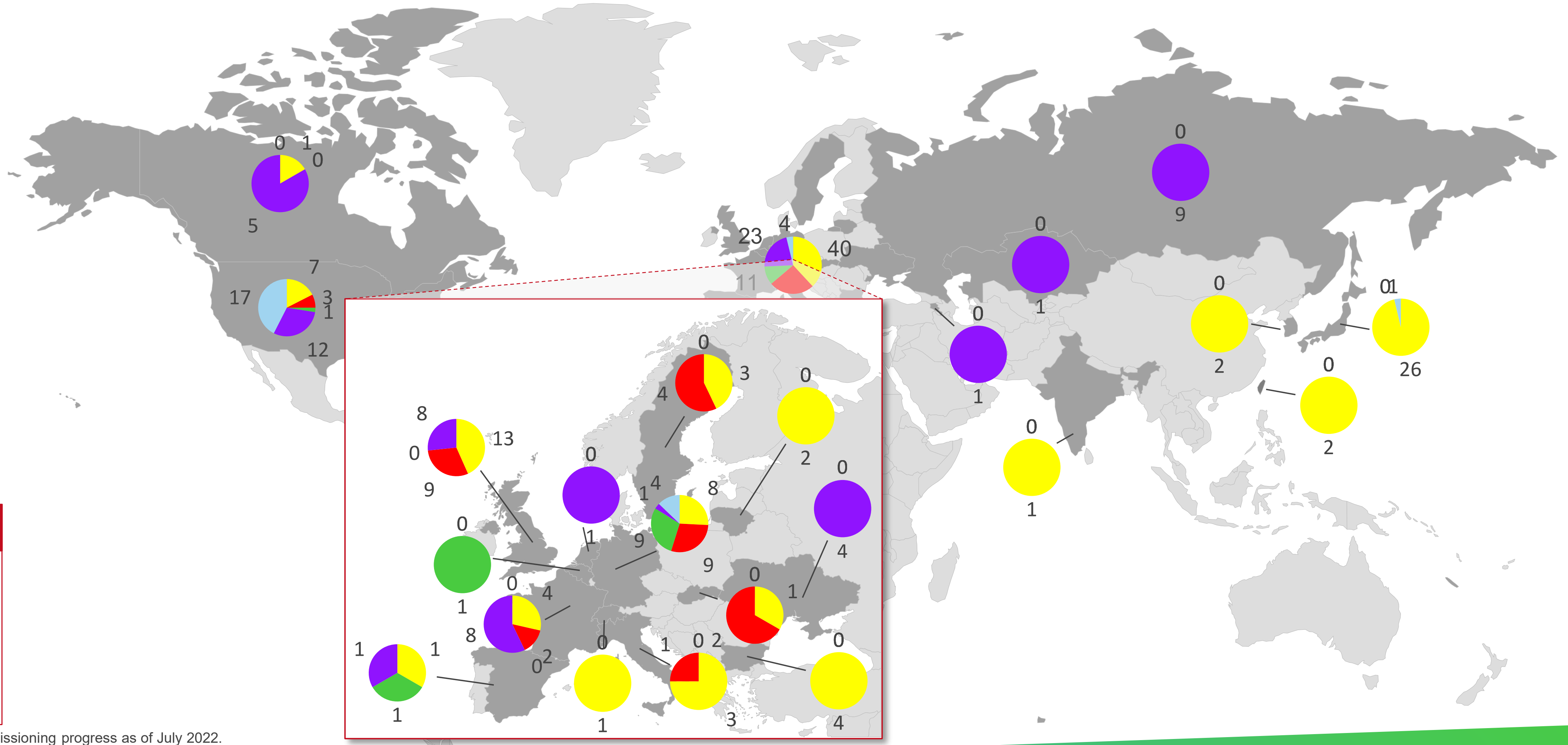
- Dismantling of remaining components and machinery
- Decontamination of buildings
- **Release from regulatory oversight**
- Demolition of buildings
  - **Greenfield**: Site released to be used in non-industrial (and non-nuclear!) context
  - **Brownfield**: Site released for industrial use, e.g., further electricity generation or interim storage facility for nuclear waste.

Sources: Schneider et al. (2022), Images: Brendebach et al. (2017)

BACK-UP

Current Status of Decommissioning Efforts

Nuclear decommissioning is ongoing worldwide, 204 reactors are closed



Key

- Warm-Up
- Hot-Zone
- Ease-Off
- LTE
- Completed

State of nuclear decommissioning progress as of July 2022.
Source: Schneider et al. (2022)

System Good Nuclear Decommissioning

Processes and Assets following Wealer and von Hirschhausen (2020, p. 46)

BACK-UP

Stage	Processes	Assets
Warm-Up	• Defueling of the reactor core and the spent fuel pools • Decontamination work • Dismantling of first redundant systems • Installation of logistics in the hot zone • Dismantling of higher contaminated plant components (e.g., steam generator and parts of the primary cooling circuit) • Conditioning work of operational wastes and spent fuel (Loading the spent fuel into storage casks)	• Transport and storage casks • Decontamination tools • Transport logistic • Logistic for handling hot-zone work • Interim storage facility • Disposal facility (or access to)
Hot-Zone	• Dismantling of the reactor pressure vessel • Dismantling of the reactor pressure vessel internals • Dismantling of the biological shield • Dismantling of the cooling circuit	• Transport and storage casks • Decontamination tools • Transport logistic • Logistic for handling hot-zone work • Interim storage facility • Highly specific tools for reactor dismantling (e.g., under water manipulator)
Ease-Off	• Removal of operating systems • Decontamination of the buildings • (ideally) the demolition of the buildings • Conditioning works • Site remediation	• Transport and storage casks • Decontamination tools • Transport logistic • Logistic for handling hot-zone work • Interim storage facility • Disposal facility (or access to)

Introducing Transaction Costs to Nuclear Decommissioning

BACK-UP

Transaction costs: Transaction costs are real resources that are required to create and operate an institution. They are not directly linked to value creation but occur when goods and services are transferred across separable interfaces. (Williamson, 1979, 1985)

Dimensions of Transactions in Nuclear Decommissioning

Uncertainty

- Unknown degree of on-site radiological contamination of buildings and components
- Structural integrity of ageing concrete structures
- …

Frequency

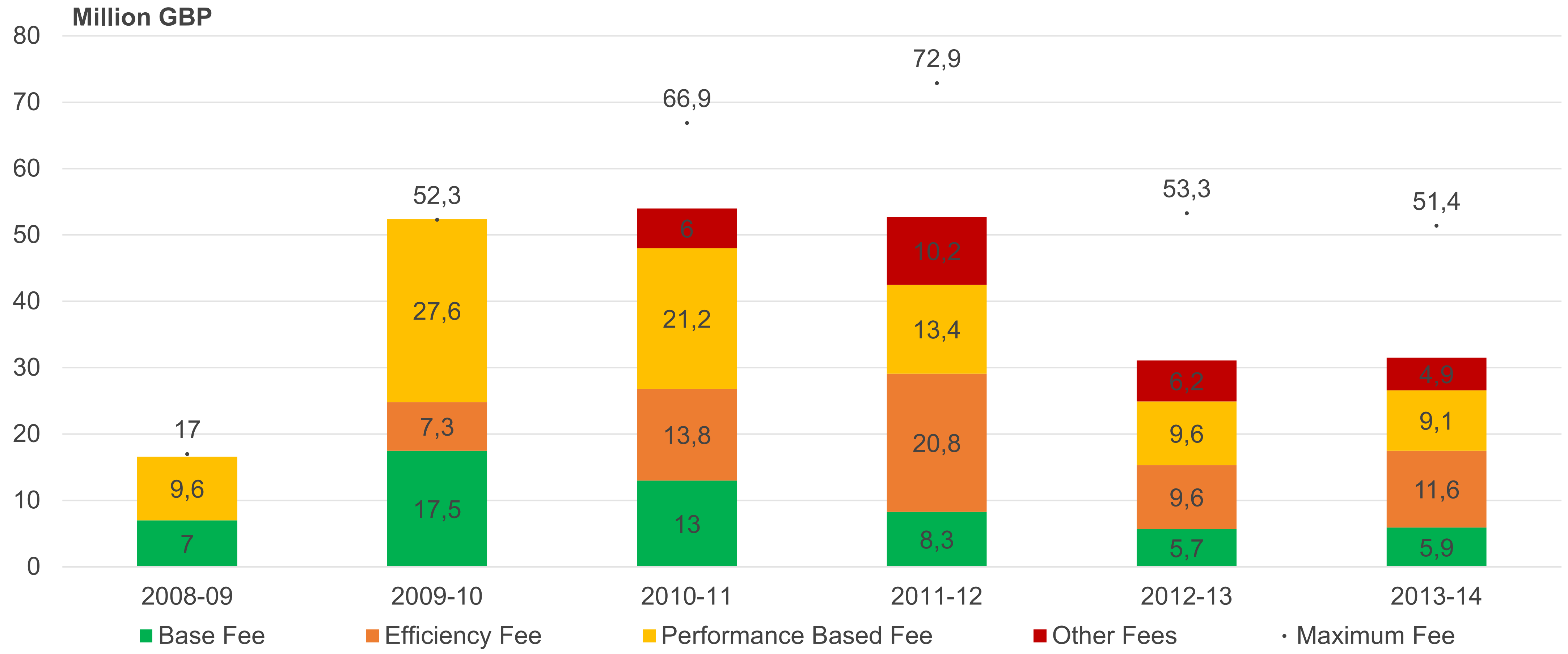
- Achievability of economies of scale through repetition of tasks and standardization uncertain
- Economies of scope limited due to complexity of radiation management
- …

Asset Specificity

- Diverse nuclear power plant fleet structures limit standardization possibilities
- Historical neglect of decommissioning necessity during construction
- Specialized tools necessary
- ….

Nuclear Decommissioning in the United Kingdom
Sellafield Fees following NAO (2015)

BACK-UP



Nuclear Decommissioning Organization in the United Kingdom
Some Transaction Costs in the PBO scheme

BACK-UP

Ex-ante TAC	Ex-Post TAC
Tendering and Contracts - Defining criteria - Setting up tendering process (weighting of criteria) - Screening of competitors - Contract design - Transfer of knowledge and property rights to new PBO	**Tendering and Contracts** - Defense against litigation: establishment of checks and balances to avoid false awarding
Monitoring Technical goals: “setting the baseline” - Gathering necessary information from SLCs - Definition of tasks that can reasonably be completed **Target Cost Approach** - Setting incentive: fee to be earned - Determining reasonable target cost for previously determined baseline - bargaining with PBO	**Monitoring** - Target monitoring - Evaluation of contract extension requesites - Reimbursement approach: are claims viable? - target cost: monitoring during the process and at the end? - New PBO beting potential lack of trust from on-site workers that may suspect lay-offs - For the return of assets at the end of the contract, the state of sites must be evaluated

Nuclear Decommissioning Organization in the United Kingdom
Some Transaction Costs in the Market-Enhanced Model

BACK-UP

Market Enhanced Model
~ costs of discovery between NDA and SLC
~ monitoring of efforts from SLCs by NDA
~ knowledge transfer between SLCs, sites and NDA

Nuclear Decommissioning Organization in the United States
License Stewardship and License Acquistion

BACK-UP

Licence stewardship	
Ex-ante	**Ex-post**
- Contract negotiation - Delivery, progress milestone? - Discovery	- Return of license and remaining DTF funds - Possible monitoring by utility after return of
Licence acquisition	
Ex-ante	**Ex-post**

- Discovery from both parties
  ○ Status of site
  ○ State of DTF (estimated value)
  ○ Determination of incentives: Can surplus DTF funds be accessed by decommissioning company?
- Negotiations
	- integration of knowledge from past sites to new site <-> knowledge transfer on-site workers to licence holder
	- establishment of new owner -> beat potential lack of trust from on-site workers that suspect lay-offs