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Nuclear Power as a System Good

Organizational Models for Production along the Value-Added Chain

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Agenda

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1) Introduction
2) Methodological framework
3) The system good nuclear power – a stylized description
4) Value-added stages and interfaces
5) Conclusion and Outlook

Nuclear Power as a System Good - Organizational Models for Production along the Value-Added Chain

Research Questions / Objectives:

- What are the governance structures after seven decades of nuclear power generation along the value-added chain of the nuclear industry?
- What is the state of the industry?
- Is there competition?

Approach:

- In this paper, we provide an institutional economic analysis of the nuclear power industry, in the context of system good analysis.
- Positive analysis of the real existing organizational and supply models for the value creation stages of the nuclear sector with respect to competition in the different value-added stages.
- For this, we look at the governance structure (Williamson 2000) of the involved companies (state, private, semi-private), their degree of vertical integration (Coase 1937; Williamson 1985), the market shares as well as the form of transaction (markets, long-term contracts).

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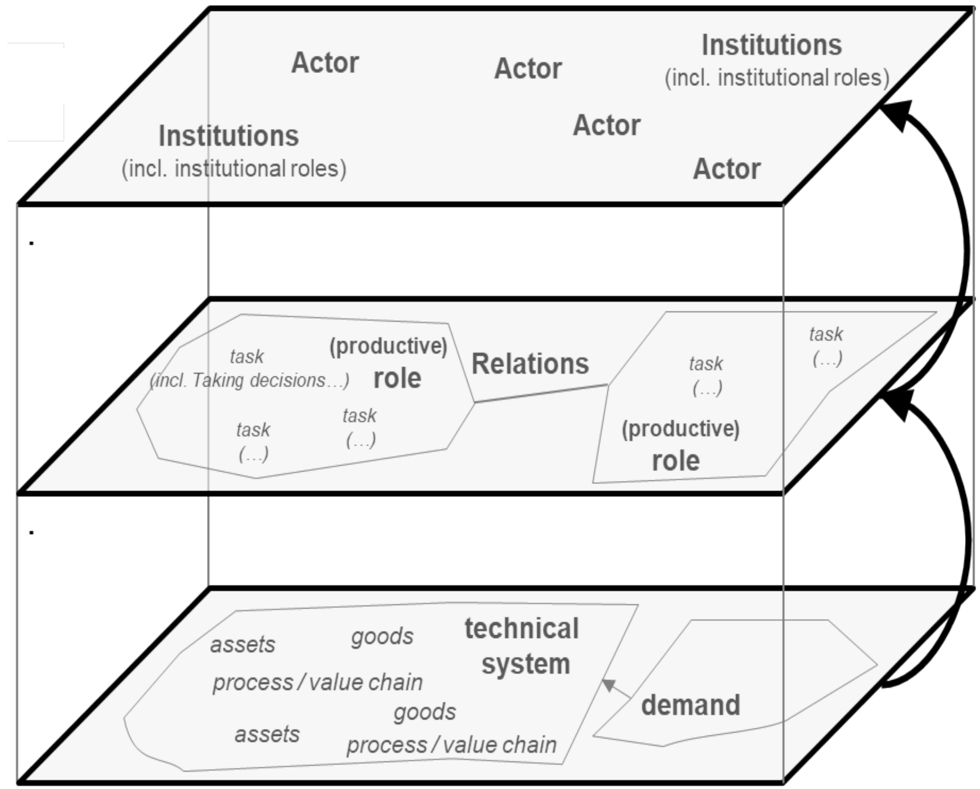
Methodological Framework: System Good Analysis developed by Beckers et al. (2012).

- **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.**



Basic assumptions and key elements.

Source: Gizzi (2016).

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

- **Production** refers to “the more technical process of transforming inputs into outputs-making a product, or, in many cases, rendering a service” (acir 1987, 7).

- **Provision** (what, when, how, how much) refers to decisions made through collective-choice mechanisms about inter alia, the kinds of goods/services; quantity and quality; how to arrange for the production (Ostrom, Schroeder, and Wynne 1993, 74).

- As **financing** is a critical part of large-scale infrastructure, we treat financing issues and responsibilities separately from provisioning and production

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The System Good Nuclear Power: A Stylized Description

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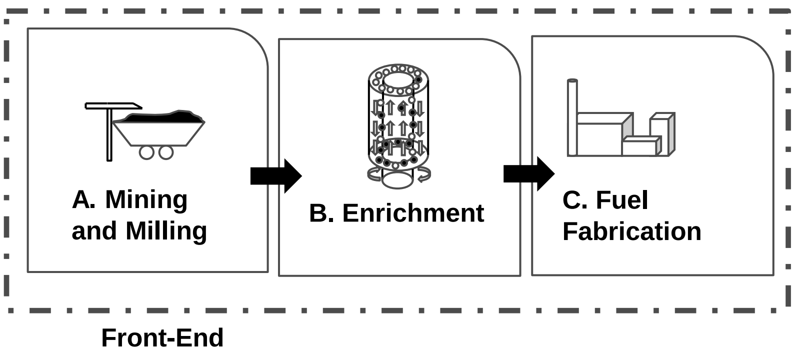

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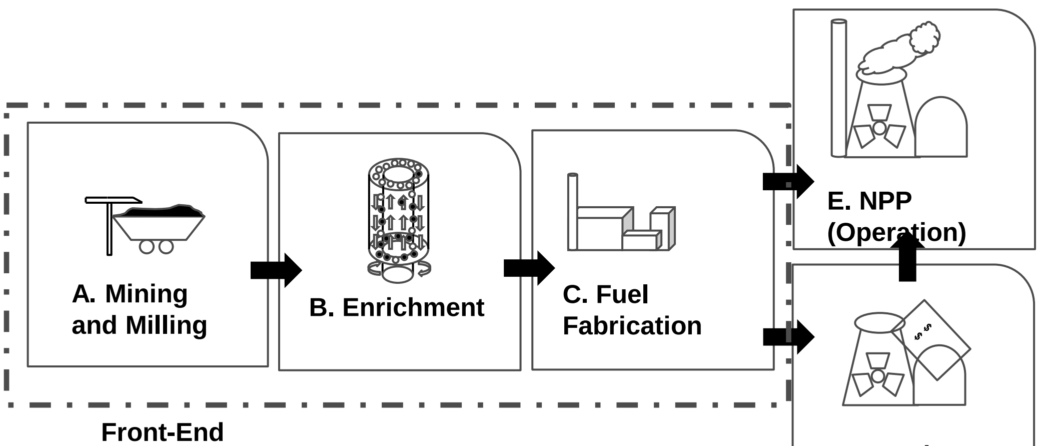

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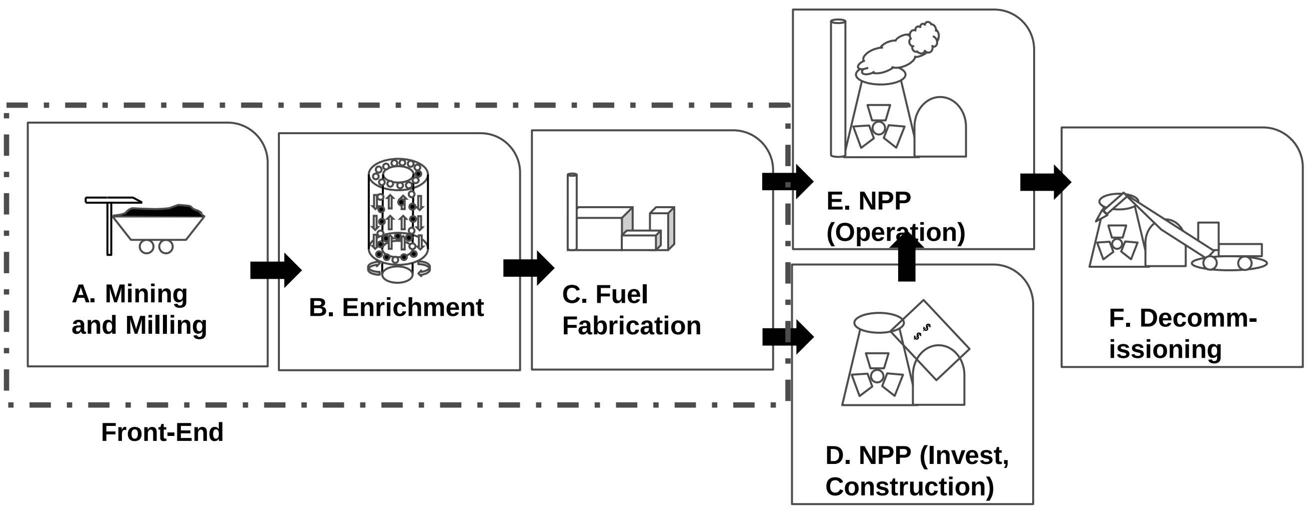
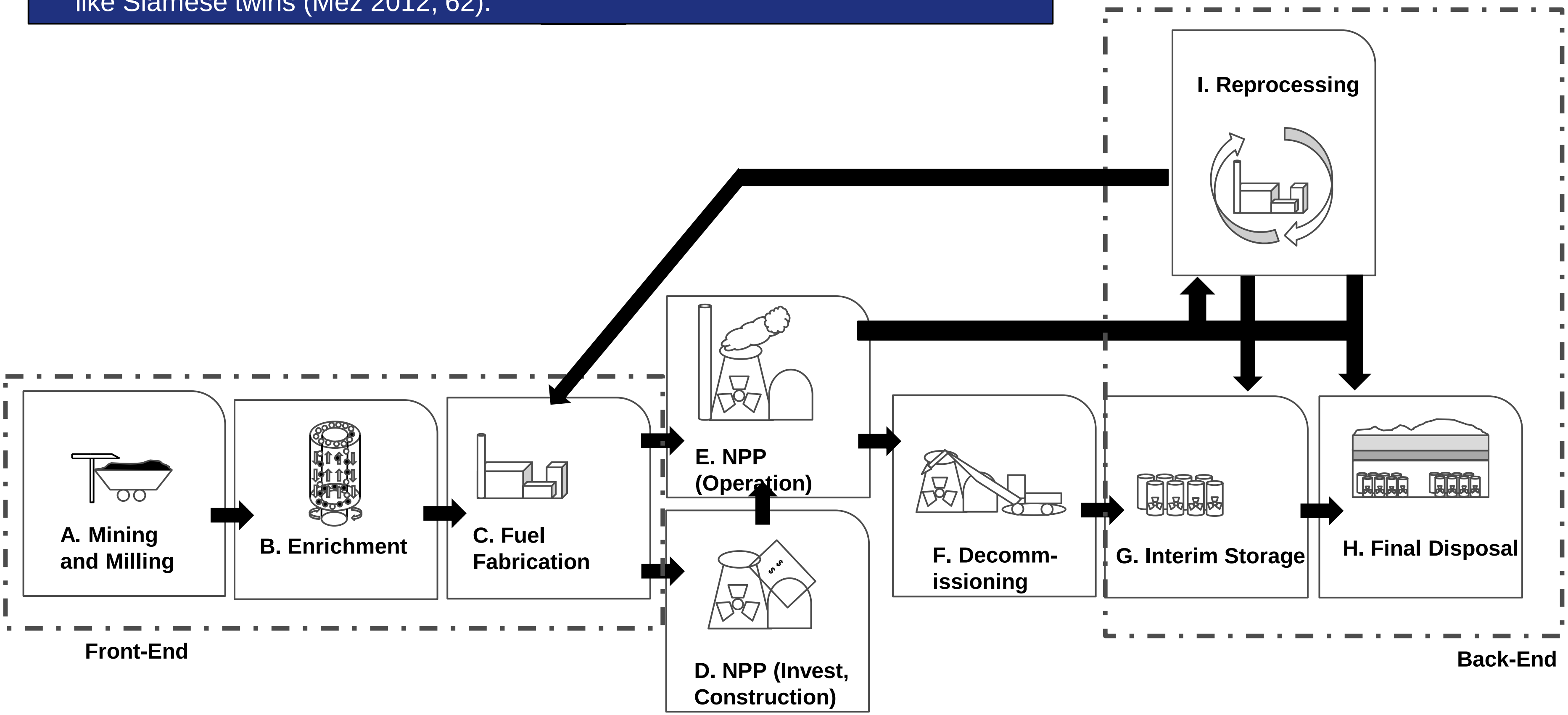


The System Good Nuclear Power: A Stylized Description

- Nuclear power is the “child of scientific research and the military” (Lévêque 2014, 212)
- The military and civil use of nuclear power are intrinsically linked to one another like Siamese twins (Mez 2012, 62).



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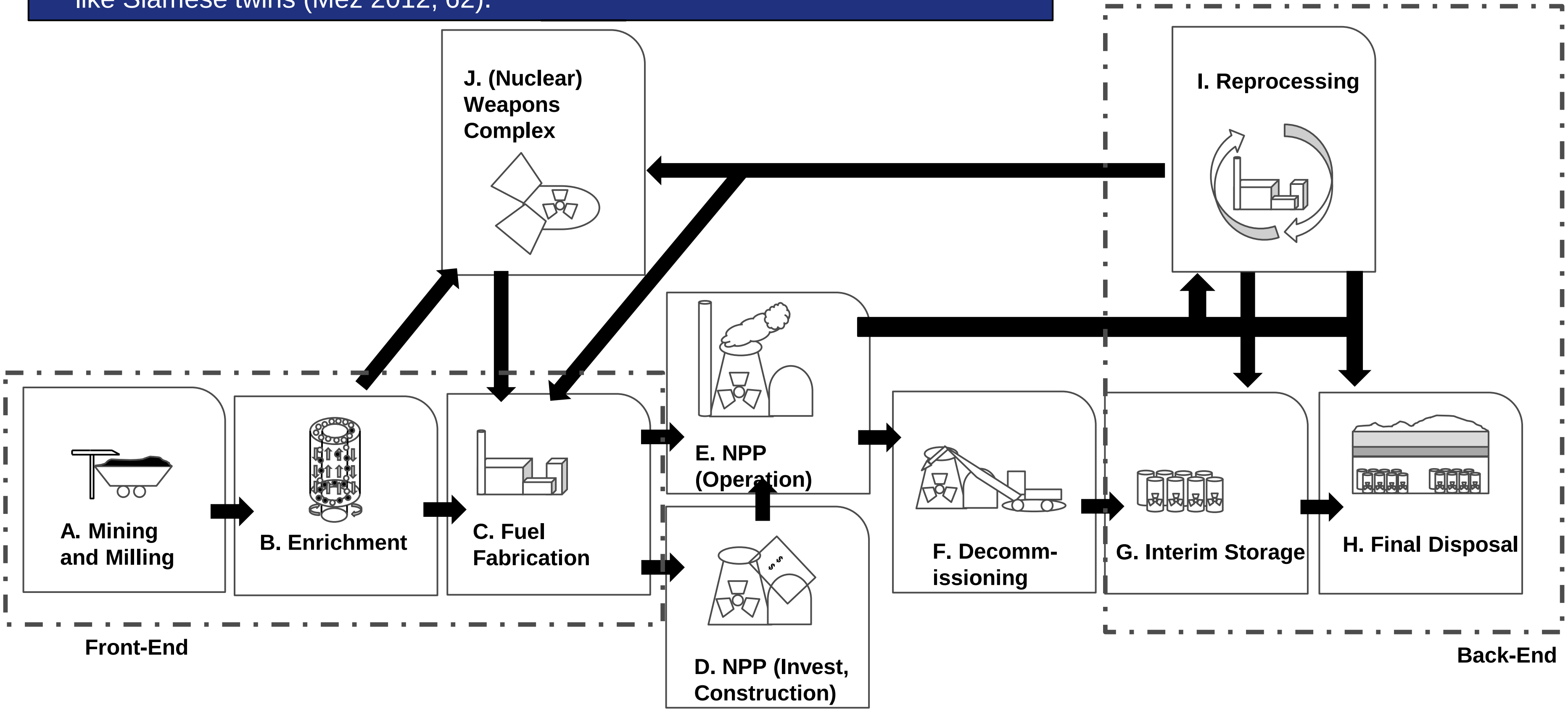

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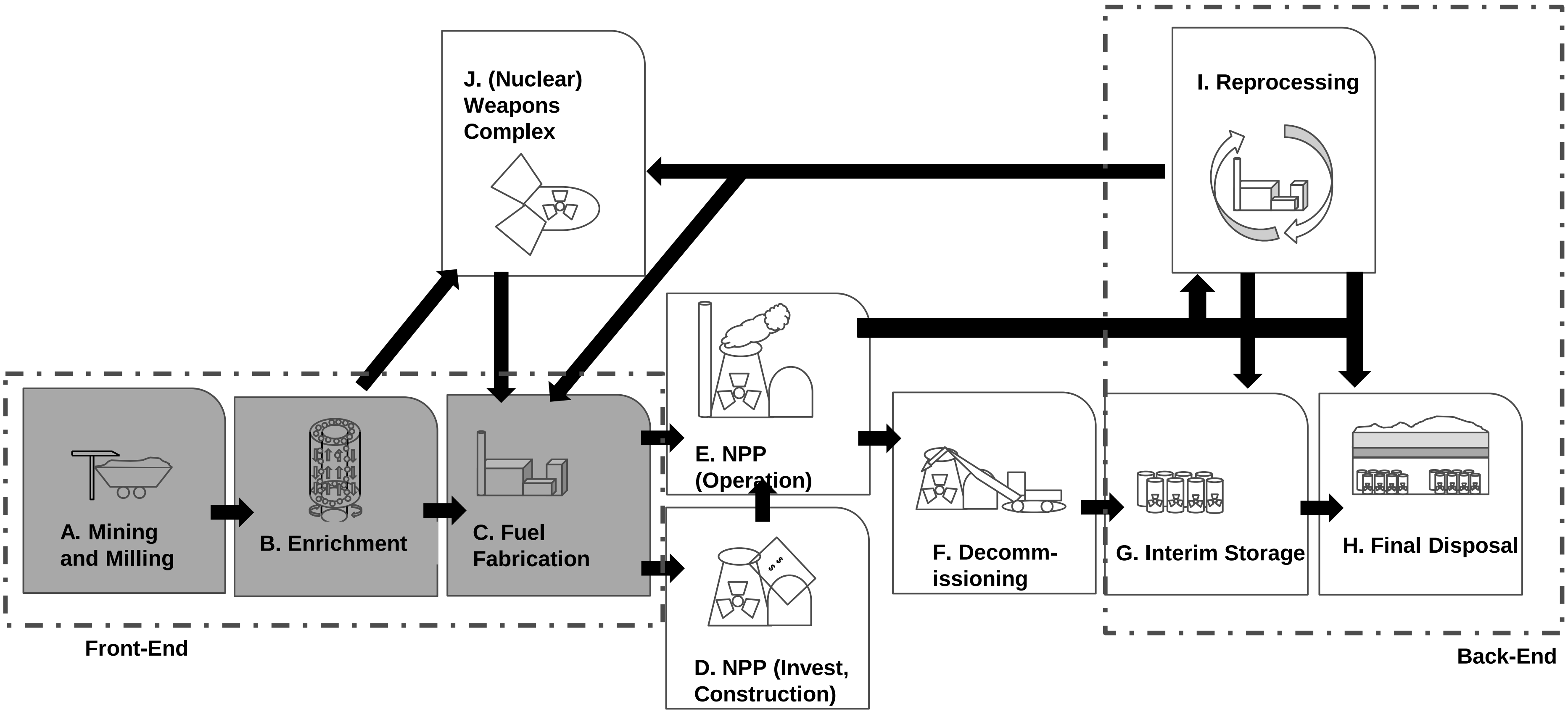


The technical system „nuclear front-end“ - summary

The analysis of the technical system leads to a picture of interdependent processes, which are mostly characterized by a high degree of specificity, a low degree of substitution, and some compatibility.

Elementary Process	Processes	Assets
Mining & Milling	• Discovery and classification of uranium deposits • Mining of uranium ore • Transporting ore to mill • Milling and leaching of ore to produce concentrated U_3O_8	• Uranium mines (or ore) • Mining infrastructure • Transport logistic
Conversion	• Conversion of U_3O_8 into UF_6	• Conversion plant
Enrichment	• Enrichment of UF_6	• Enrichment plant (e.g., centrifuge)
Fuel Fabrication	• Chemical conversion of UF_6 into uranium dioxide (UO_2), • Transformation into ceramic UO_2 pellets. • Fabrication of the metal framework for the fuel assembly • Finalizing final fuel assembly	• Fuel fabrication plant • Decontamination tools)

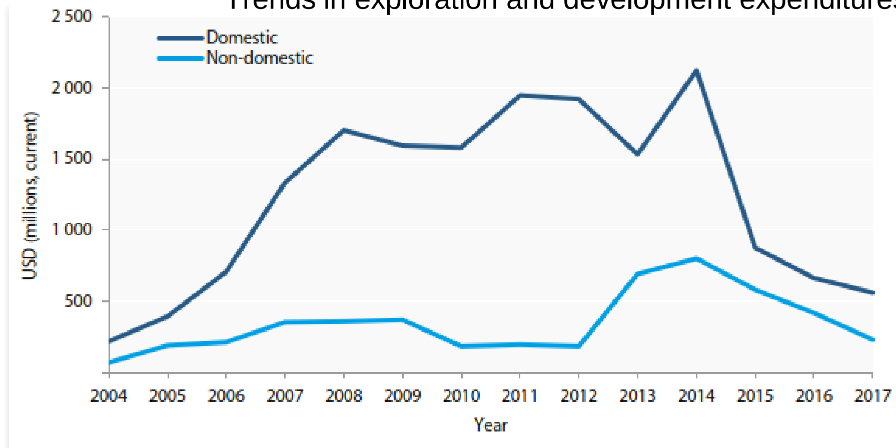
Processes and assets of the technical system “front-end. Source: Wealer and Hirschhausen (2020).

Possible areas of coordination are between the enrichment plant and the provision of the conversion service; between the nuclear utility and fuel fabrication, especially towards fuel element structure and reactor specifics.

Organization Models for Mining and Processing

- **Steady decline in spending uranium exploration and mine development**
- **Uranium deposits: ~ 6 million tons**
  - Australia has the largest share with about one third, followed by Kazakhstan
  - Three countries (Australia, Kazakhstan, and Canada) control more than 50%.
- **Market is highly concentrated with four majority-state-owned companies**
- **U.S. imports around 93% of its uranium (discussion of import quotas).**
- **Several mines are operated under joint ventures**
- **80% of the uranium deals are made under long-term contracts:**
  - Executed several years in advance of the first delivery.
  - Typically lasting for five years or in some cases ten years or more.
  - Prices can be fixed or variable (based on spot market) during the term of the contract.

Trends in exploration and development expenditures.



Source: NEA and IAEA (2018, p. 43)

Company	Main Owner	Production [tons]	Share world-wide
Kazatom-prom	The Kazakh National Wealth Fund Samruk-Kazyna JSC owns 81.28%	11,074	22%
Orano	The French State directly or indirectly controls 86,52 % of the capital.	5,809	11%
Cameco	Canadian State	4,613	9%
Uranium One	Rosatom	4,385	8%

The top four uranium mining companies, as of 2018.
Source: Own depiction based on NEA and IAEA (2018)

Organization Models for Conversion

- Operational commercial conversion plants: U.S., Canada, France, Russia, and China, Canada.
- Except for ConverDyn, the multinational US company, all conversion plants are in state ownership; although the US conversion plant has stopped its production since 2017 due to a current worldwide oversupply of uranium hexafluoride (UF6).
- The four active companies are also involved in the mining business. This vertical integration makes sense, as these companies are solely involved in the nuclear sector.
- UF6 conversion services can be bought on the spot market, but the majority of conversion supply is bought under long-term contracts between the nuclear utilities.

Company	Location (Country)	Capacity [Tons]	Capacity Utilization
Orano	Pierrelatte and Malvesi (France)	15,000	2,500 (17%)
CNNC	Lanzhou und Hengyang (China)	15,000	10,000 (67%)
Cameco	Port Hope (Canada)	12,500	10,000 (80%)
Rosatom	Seversk (Russia)	12,500	12,0000 (96%)
ConverDyn	Metropolis (USA)	7,000	0 (0%)
Top 10 total		**6,000**	**34.500**

Conversion plants and their capacity, as of 2018.

Organization Models for Enrichment

- **Until the 1980s: the “Western” market for enrichment services was monopolized by the U.S. with its diffusion process, while the USSR had the monopoly for the "Eastern" market.**
- **Since 1980s: companies with gas centrifuge technology, i.e. Russia and the British-Dutch-German company Urenco, have gained increasing market shares.**
- **Because of the inherent high risk of proliferation, only the nuclear weapon states have enrichment technologies on a commercial scale, with one exception: Urenco.**

- **Russia has by far the largest enrichment capacity, followed by France. These two companies have also vertically integrated the conversion services into their portfolio.**
- **Japanese JNFL, Chinese CNNC mainly serve the domestic market.**
- **Due to the dual-use nature and the complex institutional environment, the majority of supply is conducted under long-term contracts, often with a duration of five or more years.**

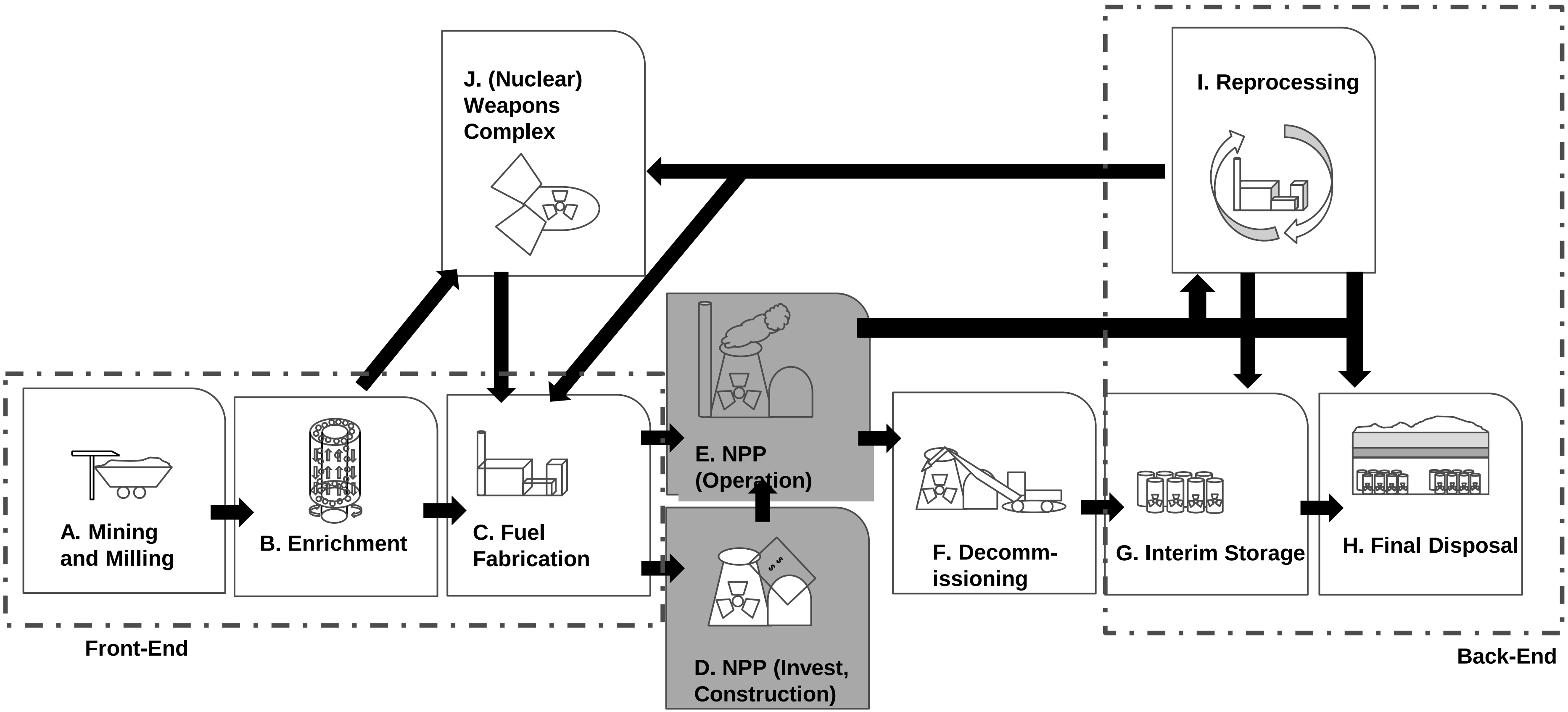
Company	Location	2013	2015	2020
Orano	Georges Besse I & II (France)	5,500	7,000	7,500
Urenco	Urenco: Gronau (DE); Almelo (NL); Capenhurst (UK).	14,200	14,400	14,900
JNFL	Rokkaasho (Japan)	75	75	75
Urenco	Urenco (New Mexico)	3,500	4,700	4,700
Tenex	(Angarsk, Novouralsk, Zelenogorsk, Seversk; Russia)	26,000	26,578	28,663
CNNC	CNNC (Hanzhun & Lanzhou; China)	2,200	5,760	10,700+
Others	Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total separative work units /year	**51,550**	**58,600**	**66,700**

Organization Models for Fuel Fabrication

- **High specificity:**
  - Fuel assemblies are highly engineered products that have to be adapted to the physical characteristics of the reactor.
  - Therefore, a large part of the fuel fabrication companies are reactor vendors (or owned by them).
- **The LWR market can be looked as three single markets: BWR, PWR, and VVER.**
- **LWR fuel market has become more competitive lately, as several suppliers can now supply most fuel types.**
- **In addition: some rationalization and formation of joint ventures.**
- **Orano and Kazatomprom agreed to build a fuel fabrication plant in Kazakhstan, the latter plans to supply 1/3 of the world fuel fabrication market by 2030.**
- **Long-term contracts.**
- **Changing the nuclear fuel supplier can have costly and regulatory consequences.**

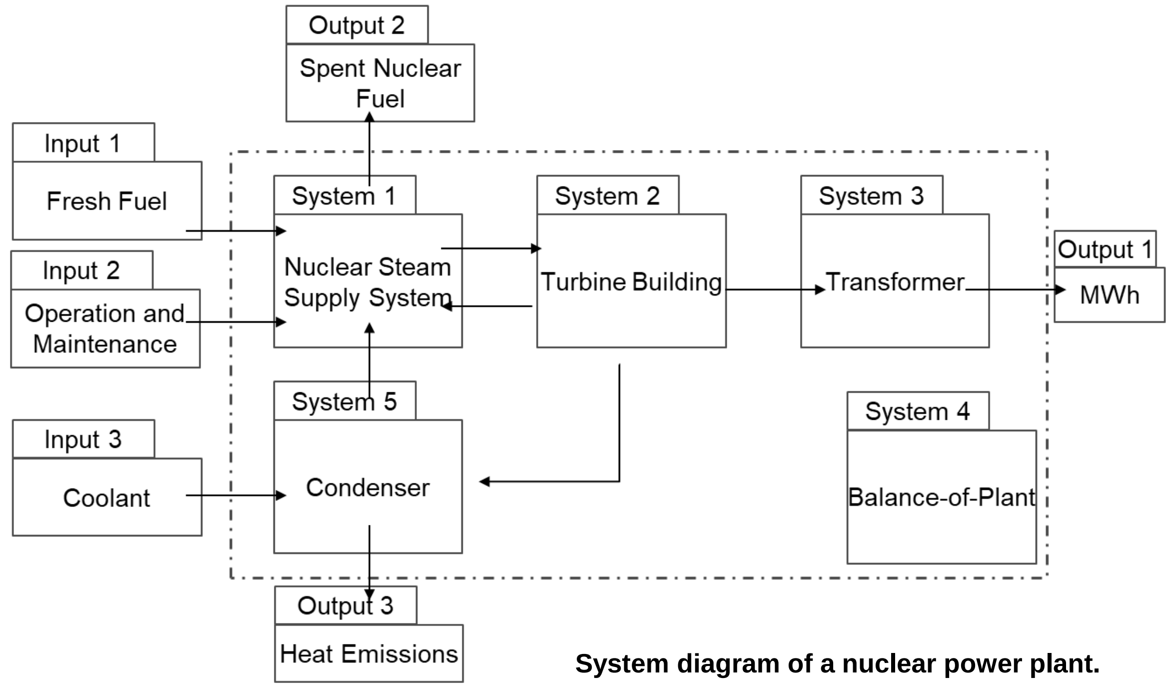
Company	Location	Con-version	Pellet-izing	Rod/as-sembly
Westinghouse AB/**/	AB: Västeras (Sweden); **: Springfields (UK); Columbia (USA)	3,337	2,794	3,614
Framatome FBFC/ANF/Inc.	FBFC: Romans (France); ANF: Lingen (Germany); Inc: Richland (USA)	3,800	3,250	3,250
TVEL MSZ*/NCCP	MSZ: Elektrostal (Russia); NCCP: Novosibirsk (Russia)	1,950	2,700	2,760
Global Nuclear Fuel Japan/Americas	Kurihama (Japan); Wilmington (USA)	1,200	1,620	1,630
CJNF Jianzhong	Yibin (China)	800	800	800
KNFC	Daejeon (Korea)	700	700	700
NFI	PWR: Kumatori (Japan); BWR: Tokai-Mura (Japan)	0	633	534
ENUSA	Juzbado (Spain)	0	500	500
Mitsubishi Nuclear Fuel	Tokai-Mura (Japan)	450	440	440
INB	Resende (Brazil)	160	120	400
CBNF	Baotou (China)	0	0	400
CNNFC	Baotou (China)	200	200	200
DAE Nuclear Fuel Complex	Hyderabad (India)	48	48	48
Ulba	Ust Kamenogorsk (Kazakhstan)	0	108	0
		12,645	**13,913**	**15,276**

The System Good Nuclear Power: A stylized description



„Construction of Nuclear Power Plants“ – Description of the Technical System

- **Several interdependent processes.**
- **The nuclear steam supply system:**
  - is often manufactured specifically for a particular reactor design.
  - Some parts require heavy forgings ingots weighing 500-600 tons) for which only a limited number of forging presses exist.
- **Identification of some other interfaces:**
  - technical interface (Input 1) exists to the fuel fabrication company with fuel elements being high-tech products designed for specific reactors.
  - Another important interface is towards the value-added stage “storage” or “disposal”, as spent nuclear fuel (output 2) needs to be evacuated from the reactor and consequently stored.



System diagram of a nuclear power plant.

Source: Own depiction based on Rothwell (2016, 3 und NRC 10 CFR §170.3

Organizational Models for „Construction of NPP “

There are three main contracting approaches for constructing nuclear power plants:

- Turnkey approach: one large contract between the reactor vendor (or consortium) and the customer covering the supply of the entire plant is drawn up. This includes everything from the design and licensing work to the moment, where the vendor hands over the “key of a working plant” over to the costumer (e.g., supply of all equipment and components, all on-site and off-site fabrication, assembly and construction work, testing and commissioning). The vendor can sub-contract work, which he is not able to supply herself.
- Split-package approach: The customer can also opt for the split-package approach, here the project is (in most cases) divided into the previously presented systems; each contracted to a different supplier.
- And multi-contract approach: The multi-contract approach gives the customer the maximum control over the design and construction of the plant, but on the other hand, she has in this approach also the most responsibility for the overall project. As only a few large nuclear utilities have the necessary resource (i.e. nuclear in-house expertise) to carry out this role, an architect-engineer will usually be contracted as the overall project manager. The architect-engineer is responsible for i.e. the overall design, licensing, contractor selection for each of the plant’s systems, for managing the actual construction work, and finally, for plant testing and commissioning (OECD/NEA 2008, 25–26).

Organizational Models for the Production of NPPs

- **The majority of the current new-build projects is situated in Asia and in the former USSR and is still done by home suppliers.**
- **The U.S. and Japan are the only two countries where "privately-owned" companies construct reactors.**
- **The top three reactor vendor countries are Russia, China, and Korea, which share over 70 percent of the world market.**
  - All three are state-owned companies
  - from a more ''centralized planning'' and less market oriented economic system with a close utility-regulatory agency connection.
  - The close connection and cooperation between the reactor vendor and the state also facilitates the export of reactors too.
  - Both, Russia and China provide a strong government backed package including financing as a policy tool.

Reactor Vendor	#constr. proj.	Share [%]	HHI
Rosatom (incl. Atomstroyexport)	17	31,48	991
CGN	8	14,81	219
KEPCO	9	16,67	278
Westinghouse	6	11,11	123
Framatome	4	7,41	55
Nuclear Power Corp. Of India	4	7,41	55
CNNC	2	3,70	14
CNNC-CGN	2	3,70	14
GE-Hitachi	2	3,70	14
Total	**54**	**100**	**1,763**

Calculation of the HHI for construction projects by reactor vendor, as of late 2017

Organizational models for the production of NPPs

- **For the construction, the degree of horizontal integration and localization is of interest.**
  - Horizontal integration gives a reactor vendor more control over production capacity and prices as he is able able to supply a high proportion of the needed components for reactor construction from its own factories.
  - The degree of localization informs about the existence of a self-reliant domestic nuclear supply chain. A high degree of localization can be observed in France, Japan, Korea, China, and Russia, while the U.K. and the U.S. have more or less abandoned localization and are dependent on imports.

- **Today, production of large components will generally be subcontracted to specialist companies.**
- **The main capacities are located in Asia, the main actor being Japan Steel Works (JSW), which accounts for 80% of the world market for large forged components for NPPs.**
- **In 2009, WH was already constrained as the RPV covers and steam generator parts for the AP1000 could only be supplied by JSW.**

Company	Country	Heavy Forging Presses [Tons]	Reactor Pressure Vessels Per Year
Japan Steel Works	Japan	14,000 x 2	12
China First Heavy Industry	China	15,000 and 12,500	5
China Erzhong & Dongfang	China	16,000 & 12,700	5
Shanghai Electric Group	China	16,500 and 12,000	6
OMZ Izhora	Russia	15,000	4
Le Creusot, Areva	France	11,300 and 9,000	-

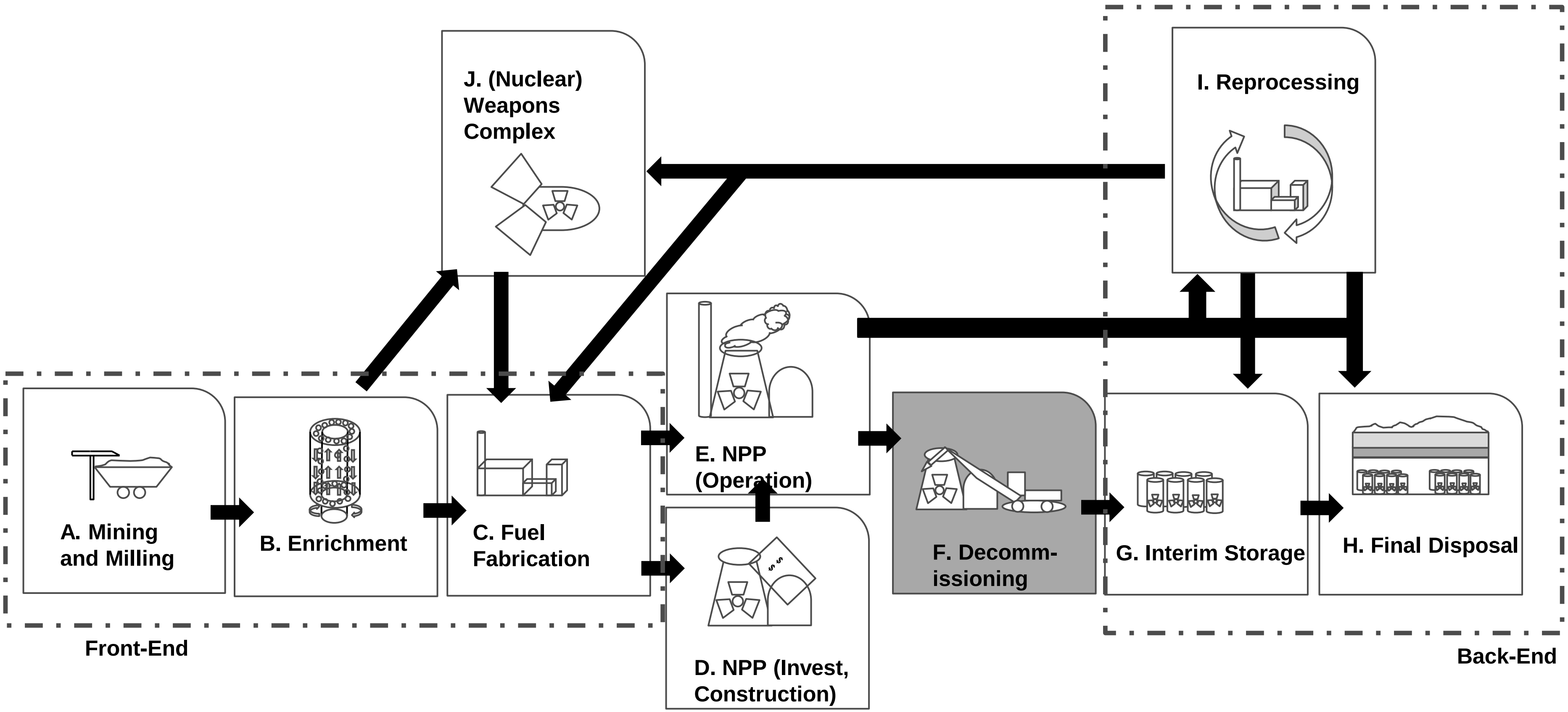
Forging companies for reactor pressure vessel production and their production capacity. Source: based on WNA (2016).

- **The WNA estimates the annual worldwide production capacity of RPVs to be sufficient for 30 large reactors (WNA 2016, 98).**

Organizational Models for Provision of NPPs

- **There is consensus on a centrally planned, state decision, since decentralized, private actors have no economic interest in such a plant (e.g., Davis 2012; Wealer, et al. 2019).**
- **Production can then be carried out by the state (integrated) or by awarding contracts to private actors in connection with regulatory agreements.**
- **Production can also be carried out in joint venture agreements, e.g. CGN/EDF for the construction of the Taishan EPR in China or EDF/CGN for Hinkley Point C in the UK).**
- **Other forms of government financing mechanisms can include:**
  - additional cost recovery rates or surcharges on electricity sales (e.g., Vogtle project in Georgia, USA),
  - loan guarantees (e.g. Vogtle project),
  - guaranteed long-term electricity contract agreements (e.g. Hinkley Point C).
- **In general, the complex nature of a nuclear power plant requires a considerable degree of "after sales" service from the vendor.**
- **In most cases, the vendor also supplies fuel services, as the majority of the major vendors (e.g. Westinghouse, Rosatom, Framatome) have vertically integrated fuel companies into their firm structure.**
- **Most reactor vendors also provide maintenance and replacement services during the reactor's lifetime.**

The System Good Nuclear Power: A stylized description

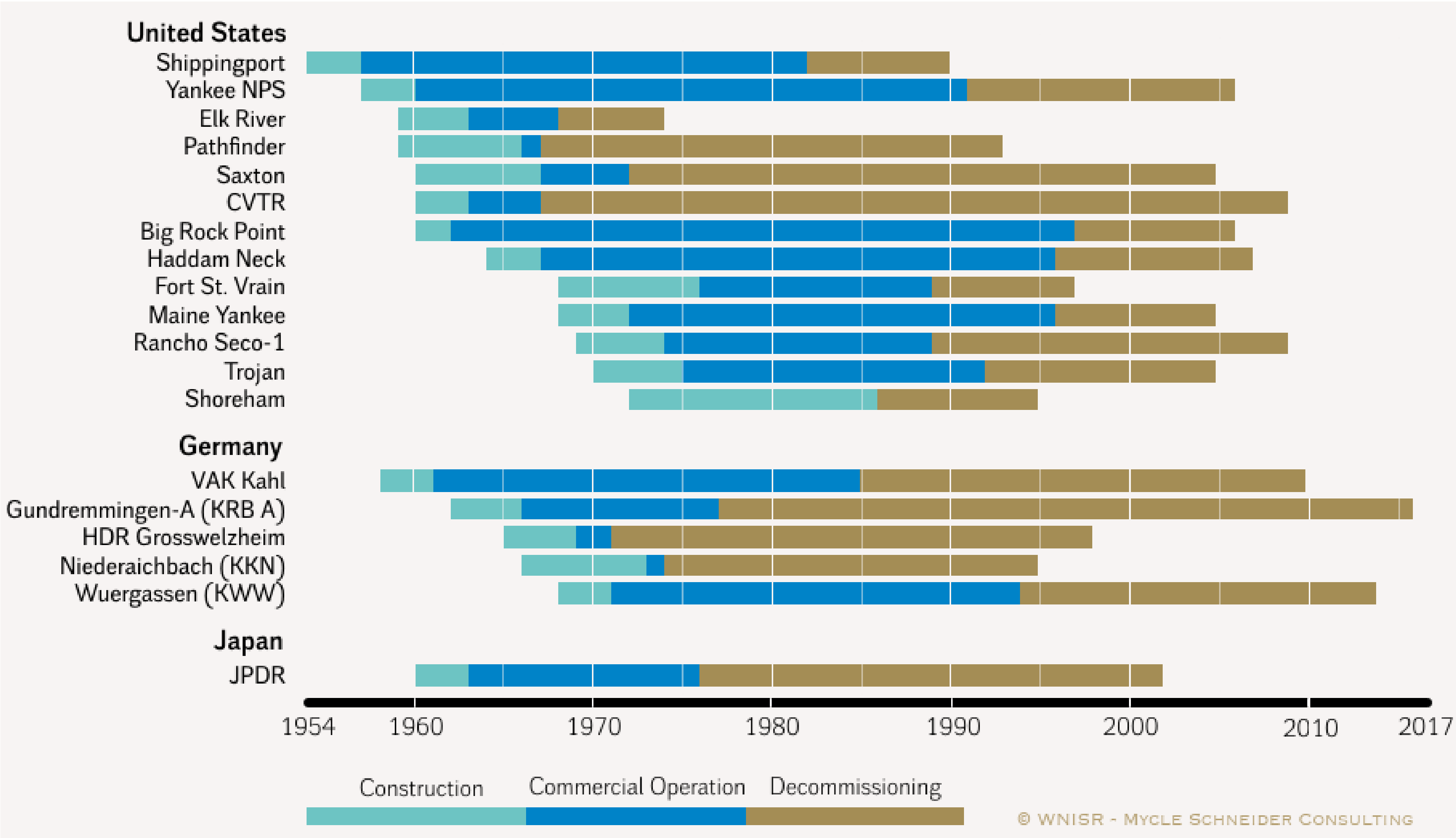


Global Survey – Little Progress in Decommissioning

Country	Closed reactors	Decommissioning Process				
		Warm-up	Hot Zone	Ease-off	LTE	Completed
Canada	6	0	0	0	6	0
France	12	3	1	0	8	0
Germany	29	10	4	8	2	5 [17%]
Japan	25[1]	20	0	0	0	1 [4%]
United Kingdom	30	0	0	0	30	0
United States	34	4	0	5	12[2]	13 [38%]
Total	**136**	**4**	**5**	**13**	**58**	**19**

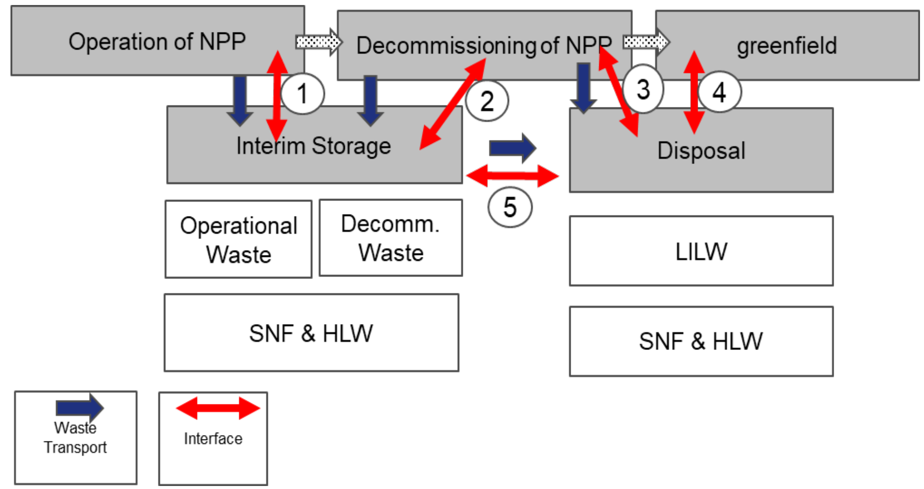
[1] Not including the Fukushima Daini 1-4 reactors. [2] 3 of which are in entombment.

Decommissioning Takes Much Longer Than Expected, In Some Cases Even Longer Than Construction and Operation Combined



Interfaces Between Value-added Stages Need Coordination

- **Interface 2** between decommissioning and interim storage in **Germany**:
  - DE: public company BGZ took over the on-site interim storage facilities of SNF and gradually of LILW.
  - Coordination between conditioning of wastes (private) and storage (public).



- **Interface 3** between decommissioning and low-and intermediate level waste disposal:
  - **U.S**: available waste disposal infrastructure facilitates disposal.
  - **Germany**: Würgassen cannot be released from regulatory control as buildings are used for LILW interim storage.
- **Interface 4** between greenfield and spent nuclear fuel disposal in the **U.S**:
  - Lack of coordination between utilities and Department of Energy (responsible for the management of spent nuclear fuel).
  - No full regulatory release possible but the site license might be reduced to the independent spent fuel storage installation.

New development in the U.S: License Transfer to Third-party Decommissioning Contractors

- First license transfer at Zion in Illinois: Exelon transferred the operating license to EnergySolutions.
- This organizational gains momentum as more and more licensees sell their licenses to emerging decommissioning contractors: EnergySolutions, Holtec International (and SNC Lavalin), or Northstar / Orano joint-venture.
- <u>Possible advantages</u>:
  - Reap efficiency gains through the (co-)management of the decommissioning process by a company owning disposal facilities (interface 3 Decommissioning – low-and intermediate level waste disposal),
  - or constructing spent fuel installations or in the case of Holtec even construct a centralized interim storage facility (interface 2 Decommissioning – spent nuclear fuel interim storage).
  - Economies of scale with one company dismantling multiple units.
  - Speed up the decommissioning processes.
- <u>On the other hand</u>, the success of this model relies on the contract design and the appropriate allocation of risks. A major concern is the allocation of the financial risk of cost overruns. In fact, if the decommissioning funds are exhausted, such a third-party company could declare bankruptcy, leaving the bill for the taxpayer.

At the Value-added Stage “Decommissioning”, Approaches to Competition Have so Far Not Been Successful

- **Decommissioning is still largely unexplored, but of increasing importance.**
- **At the value-added stage “decommissioning”, approaches to introduce competition and incentive regulation have so fare not been successful.**
- **Competitive approaches to dismantling have had little effect so far.**
- **The U.K. tried to tender the decommissioning work of its legacy fleet competitively but this failed. Now, the National Decommissioning Authority itself handles decommissioning of the Magnox sites as well as Sellafield.**
- **In the U.S., some market competition is emerging.**
- **Overall, introducing competition into the decommissioning process was unsuccessful for many reasons, such as the extreme complexity of the sites resulting from several decades of civil and (in the case of Sellafield) military nuclear activities and very long timeframes.**

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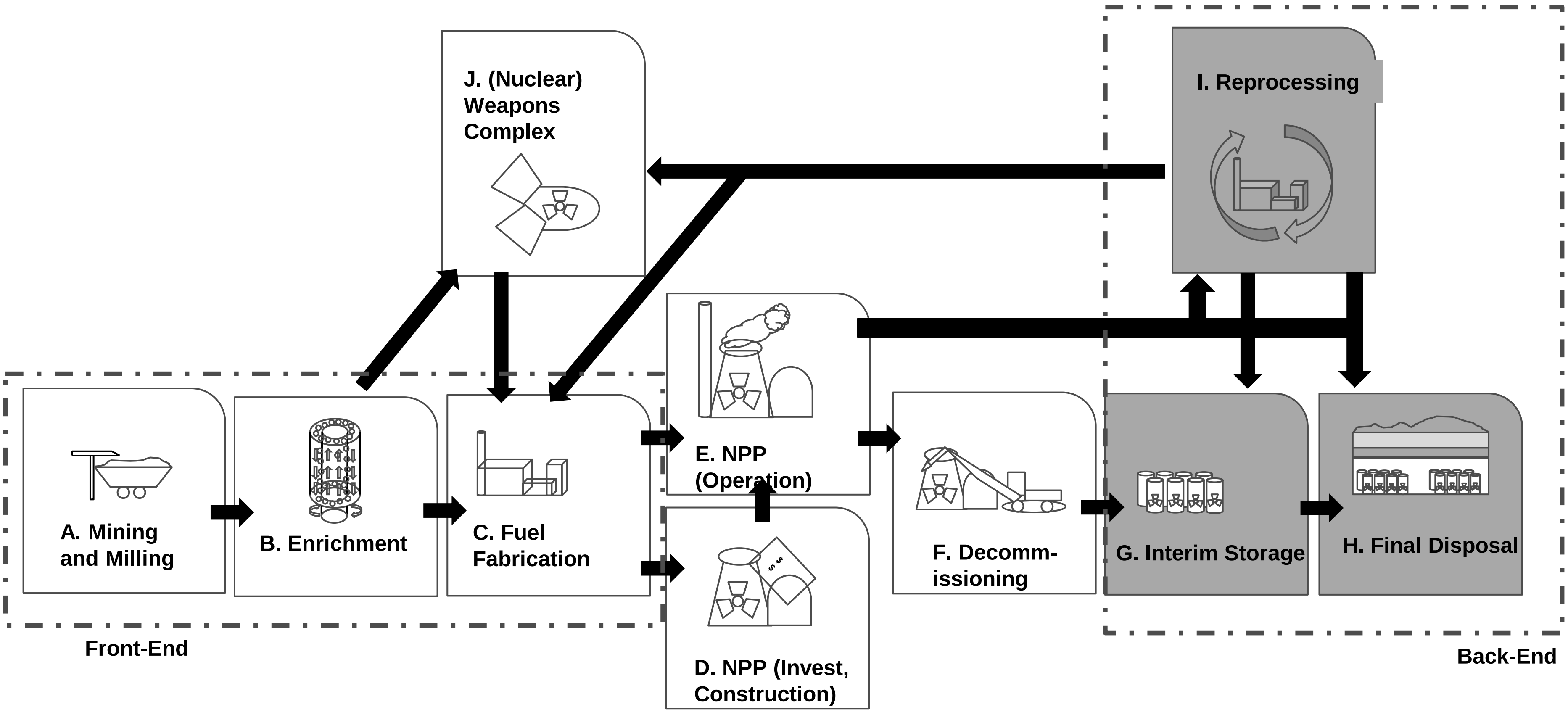


Organizational Models for Low- and Intermediate-level Waste Management

- **Disposal facilities for low-level wastes have been implemented in some countries for decades; mainly specific landfill disposal and engineered trenches, near surface disposal and belowground facilities.**
- **Belowground facilities for LILW were constructed in e.g. Sweden, and France, while in Spain (El Cabril) and the Czech Republic mines are used for disposal of LILW.**
- **The majority of low- and intermediate-level waste disposal facilities are constructed and operated by state agencies or public companies (e.g., Andra in France; Enresa in Spain; BGE in Germany; Radioactive Waste Management Ltd (RWM), which is owned by the public body NDA, in the UK).**
- **In some cases, the waste management organization is a private company (e.g., in Sweden, the utilities have created the private company SKB, the Swedish Nuclear Fuel and Waste Management Company, to operate the disposal facilities).**
- **In the U.S., some private companies are operating disposal facilities, among them EnergySolutions, a major nuclear waste management company.**

Organization models for Reprocessing

- As reprocessing means the extraction of plutonium, there is no real “civil” or “private” provider of reprocessing services and all reprocessing service providers are state-controlled.
- Western countries had to send or still send their SNF abroad for reprocessing to either France, or the UK, while Russia (and the USSR) provided this service to a few central European countries.
- In 2018, the THORP facility in the UK ceased operations; leaving La Hague in France as the last commercial reprocessing plant in Western Europe.
- Orano has a monopoly position and has thus with the exception of disposal of nuclear waste services fully integrated the nuclear front- and back-end in its firm. The same holds true for Atomenergoprom, part of Rosatom.
- Reprocessing contracts are settled through long-term contracts. One reason is the long period from unloading of SNF from the reactor core, through reprocessing, MOX fuel fabrication, and return of vitrified waste; another is the high specificity and costs for commissioning of a reprocessing plant.
- In Europe, reprocessing is still done in France, the Netherlands, and Russia, although most countries have suspended or stopped it, mainly for economic reasons (Belgium, Bulgaria, Germany, Hungary, Sweden, Switzerland, UK) (Besnard et al. 2019)

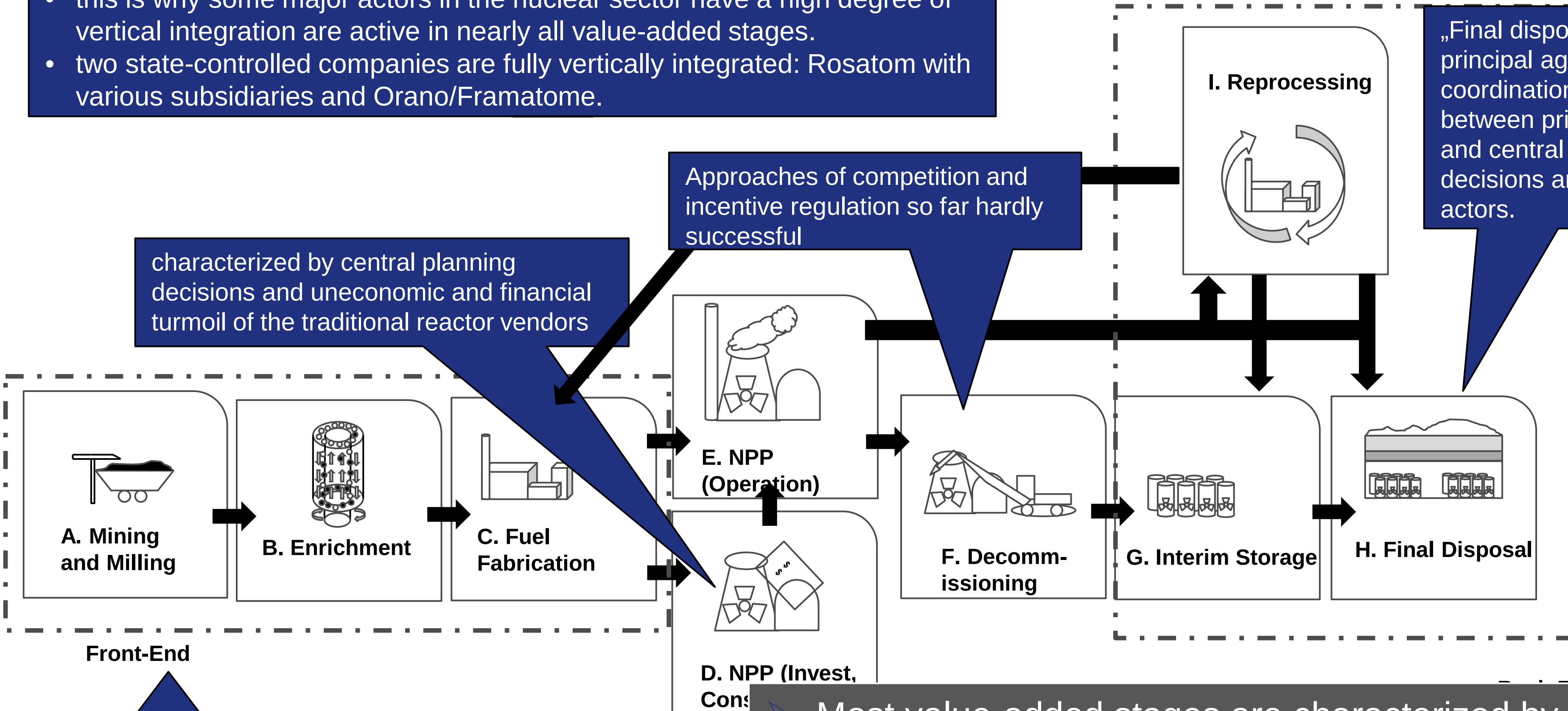
Organizational Models for High-level Waste Management

- **The final disposal of high-level waste is normally the responsibility of a special government agency or other approved body established for this purpose (OECD/NEA 2008, 91).**
- **There are exceptions to this, for instance, in Sweden and Finland the nuclear utilities created a private company for managing SNF (interim and disposal).**
- **As there is still no disposal facility available worldwide, interim storage issues are coming to the fore.**
  - Interim storage is often the scope of the utilities, while the disposal is in the hands of the national governments.
  - In the majority of the countries, SNF is stored in a decentralized way, mostly at the reactor site, either in casks (dry storage), or in spent fuel pools.
- **An important actor in the waste management services are the cask producers.. The main actors are the German utilities-owned GNS (Gesellschaft für Nuklear-Service mbH), which produces the CASTOR casks, French Orano, and US Holtec International.**
- **As disposing with nuclear waste is mostly a national matter and done by in the majority of the cases by state-controlled companies or public bodies, there is no real competition in this value-added stage.**
- **There is some competition with regard to specialized waste management companies providing casks or conditioning services. The forthcoming process of final disposal is dominated by the state worldwide and places special demands on regulators due to multiple principal-agent problems.**

Agenda

The System Good Nuclear Power

Nuclear power is one of the most complex system good imaginable:
- a multitude of overlapping and interdependent value-added stages
- the different interdependent value-added stages need coordination;
- this is why some major actors in the nuclear sector have a high degree of vertical integration are active in nearly all value-added stages.
- two state-controlled companies are fully vertically integrated: Rosatom with various subsidiaries and Orano/Framatome.



„Final disposal“ with many principal agent problems, coordination needs between private actors and central planning decisions and state actors.

Approaches of competition and incentive regulation so far hardly successful

characterized by central planning decisions and uneconomic and financial turmoil of the traditional reactor vendors

dominated by long-term contracts and a high degree of vertical integration

- Most value-added stages are characterized by integration, often state ownership, state regulation, and little competition (more hierarchies than markets).

Outlook

- Clearly, the nuclear industry lends itself well for institutional economic analysis, including reflections on the industrial economic structure, and the role of competition and regulation.
- The latter questions have so far played a negligible role in the current economic policy debate about nuclear power, and should be given greater emphasis in further economic policy research.
- In this paper, we have identified specific regulatory challenges for the back-end, in particular upstream and downstream of the decommissioning of reactor.
- More in-depth research is required to foster independent expertise on these and other matters of the complex system good nuclear power.

- Discussion paper available at: https://www.diw.de/de/diw_01.c.794003.de/publikationen/diskussionspapiere/2020_1883/nuclear_power_as_a_system_good__organizational_models_for_production_along_the_value-added_chain.html

Thank you for your attention!

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Backup

The ten biggest uranium mines, as of 2018

Mine (country)	Main Owner	Production [tons]	Share worldwide
Cigar Lake (Canada)	Cameco/Orano	6,924	13 %
Olympic Dam (Australia)	BHP Billiton	3,159	6 %
Husab (Namibia)	Swakop Uranium (CGN)	3,028	6 %
Inkai, sites 1-3 (Kazakhstan)	Kazaktomprom/Cameco	2,643	5 %
Rössing (Namibia)	Rio Tinto	2,102	4 %
Budenovskoye 2 (Kazakhstan)	Uranium One/Kazatomprom	2,081	4 %
Tortkuduk (Kazakhstan)	Orano/Kazatomprom	1,900	4 %
SOMAIR (Niger)	Orano	1,783	3 %
Ranger (Australia)	Rio Tinto/ERA	1,695	3 %
Kharasan 2 (Kazakhstan)	Kazatomprom	1,631	3 %
Top 10 total		**26,946**	**51 %**

Technological Trends of Gen III/III+ investments (as of 05-2020)

- Only 24 NPPs or 26 GW connected to the grid (~ 7% of current operational capacity).
- Supply side: majority supplied by Rosatom (Gen III to foreign markets, Gen III to homemarket).
- In early 2020: Only China and Russia operate Gen III+ reactors.

Reactor Designs	China	Japan	Russia	India	Korea	Iran	Total	Supplier
Gen III	***6***	***4***		***2***	***2***	***1***	***15***	
ABWR		*4*					*4*	GE/Hitachi/Toshiba
ACP-1000	*2*						*2*	China
AES-91	*4*						*4*	Rosatom
AES-92				*2*		*1*	*3*	Rosatom
APR-1400					*2*		2	KEPCO
Gen III+	***6***	***0***	***3***	***0***	***0***	***0***	***9***	
AES-2006			*3*				*3*	Rosatom
AP1000	*4*						*3*	Westinghouse
EPR-1750	*2*						*2*	Framatome
Total	***12***	***4***	***3***	***2***	***2***	***1***	***24***	

Country	Number of reactors	Installed capacity [MW]	Construction Period	Average Construction Duration [years]
China	*12*	*13,280*	1999-2019 (Gen III); 2009-2018 (Gen III+)	*7.2 (overall); 5.6 (Gen III); 8.9 (Gen III+)*
India	*2*	*1,834*	2002-2016	*12.9*
Iran	*1*	*915*	1975-2011	*36.4*
Japan	*4*	*5,063*	1992-2005	*3.6*
Korea	*2*	*2,680*	2008-2019	*8.5*
Russia	*3*	*2,228*	2008-2019	*9.1*
Total	***24***	***26,000***		**Average: 8.7**

- First Gen III reactor connected to the grid in 1996 in Japan.
- Average construction time for third generation reactors increased from 7 years in China to 13 years in India.
- Average construction was around 8.7 years.

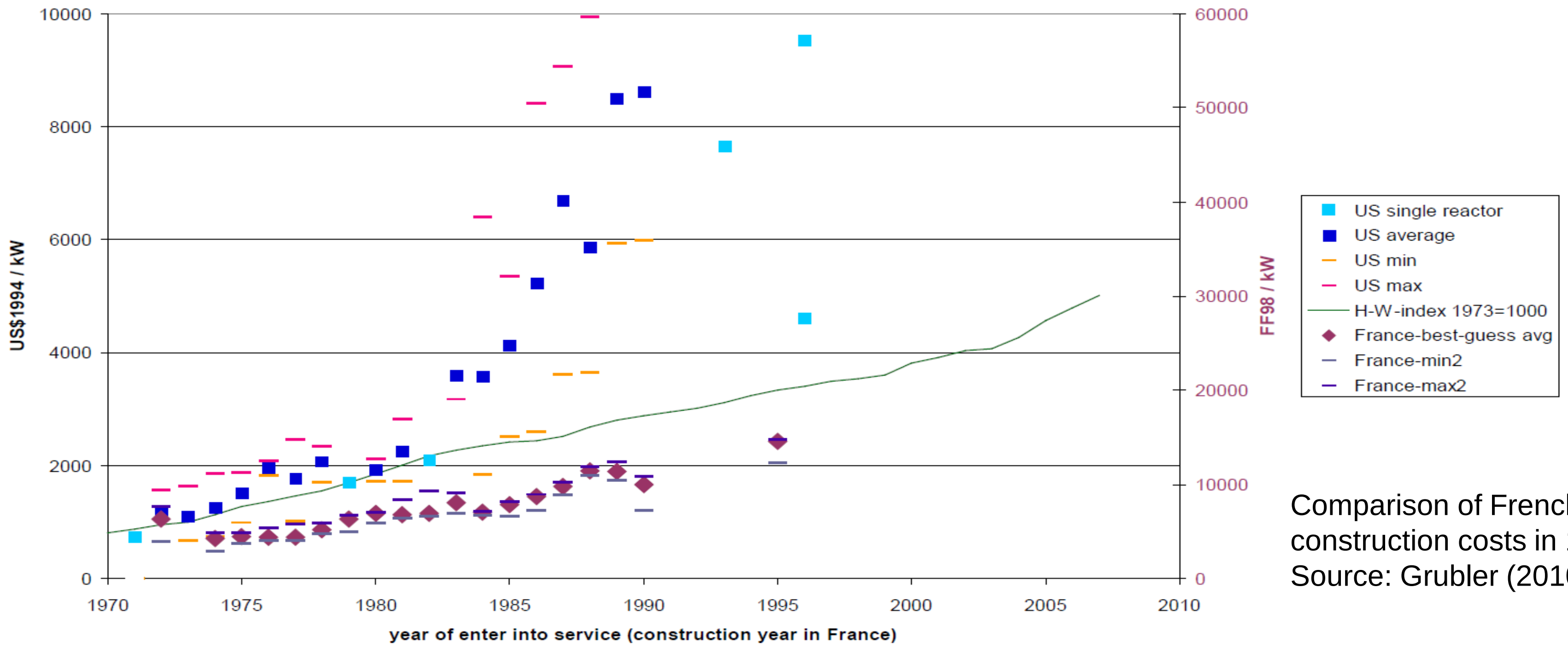
Not One Gen III/III+ Reactor Was Completed in the Western Economies.

- Not one third generation reactor was completed in the Western economies.
- Initial construction durations of around five years increased at least threefold.
- Initial cost estimations increased by ~ 25-370%.
- Construction of two other AP1000 reactors was started in 2013 at the Summer site in South Carolina but the project was abandoned in July 2017 after four years of construction.
- Major supplier: Framatome.

Site	Reactor	Capacity in MW	Construction start	Original / latest estimated construction end	Original / latest cost estimate USD_{2018}/kW
Olkiluoto-3	*EPR*	*1.600*	*2005*	*2009 / 2021*	*3,111-3,422 / 7,750*
Flamanville-3	*EPR*	*1.600*	*2007*	*2012 / 2022*	*3,300 / 9,000*
Hinkley Point C-1	*EPR-1750*	*1.630*	*2018*	*2025*	*6,750 / 8,300*
Hinkley Point C-2	*EPR-1750*	*1.630*	*2019*	-	
Vogtle-3	*AP-1000*	*1.117*	*2013*	*2016 / 2021*	*2,350 / 11,000*
Vogtle-4	*AP-1000*	*1.117*	*2013*	*2018 / 2022*	

Overview of Gen III/III+ construction projects in the European Union, U.K., and the U.S., as of 13th of March 2020.

Nuclear power plants are historically characterized by high construction costs

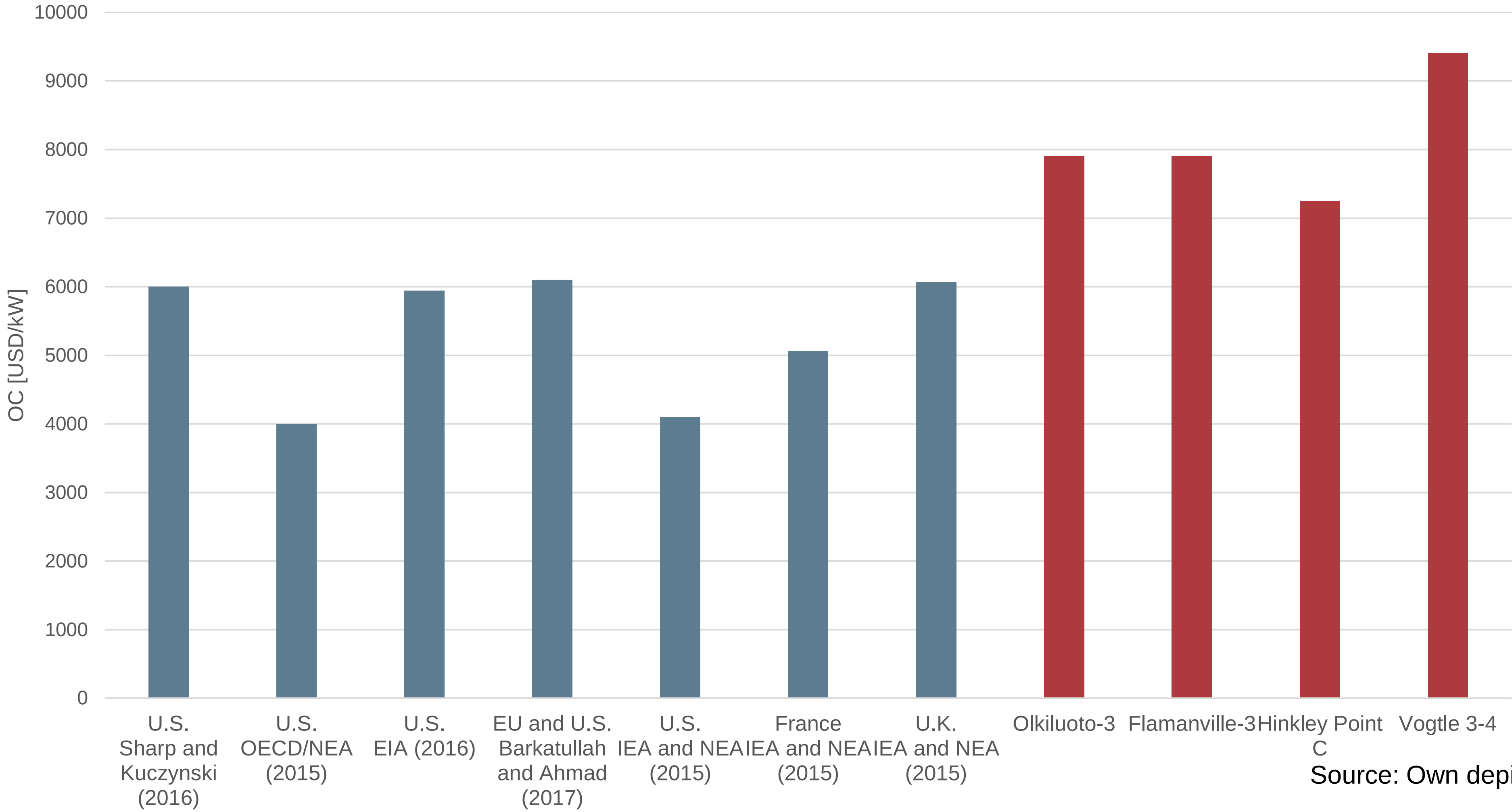


Comparison of French and US construction costs in 1994 USD
Source: Grubler (2010)

The low historical costs in France illustrate the impacts of <u>different institutional settings</u>. 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 <u>integrated "home suppliers"</u>.

Some cost estimates for Gen III/III+ reactors in the US and Europe and cost estimates for ongoing new build projects



Source: Own depiction

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:

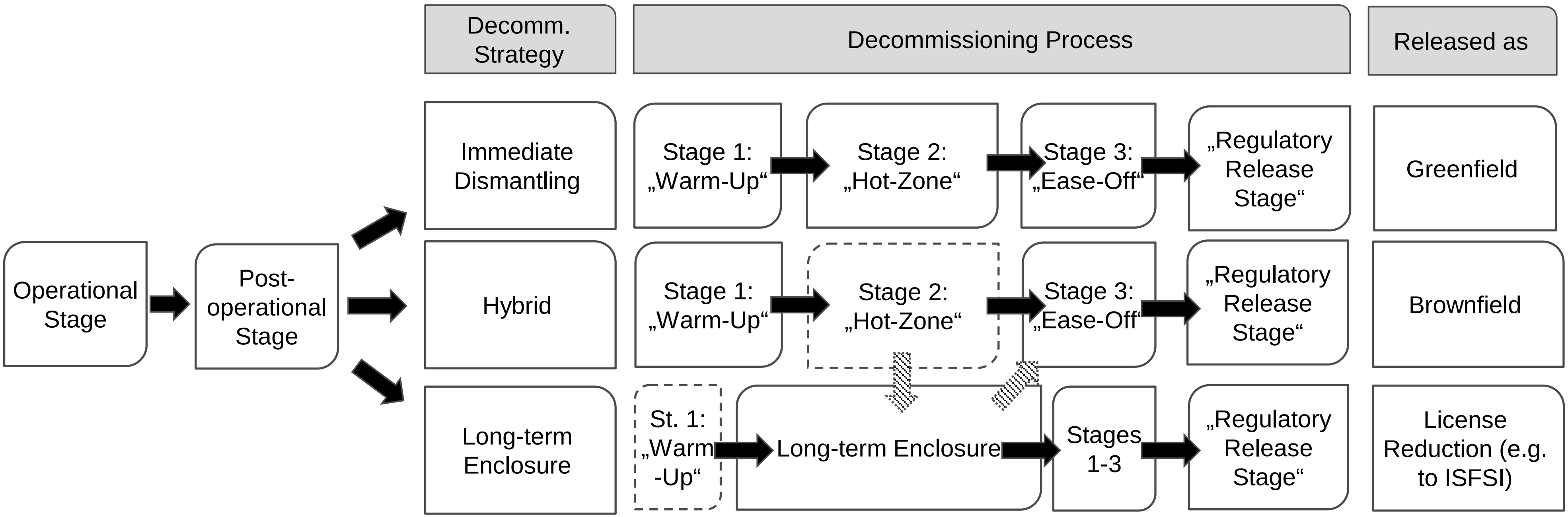
  - Westinghouse filed Chapter 11 bankruptcy protection in the US. and was acquired by Brookfield Business Partners for 4.6 billion USD from Toshiba Corporation in January 2018.

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

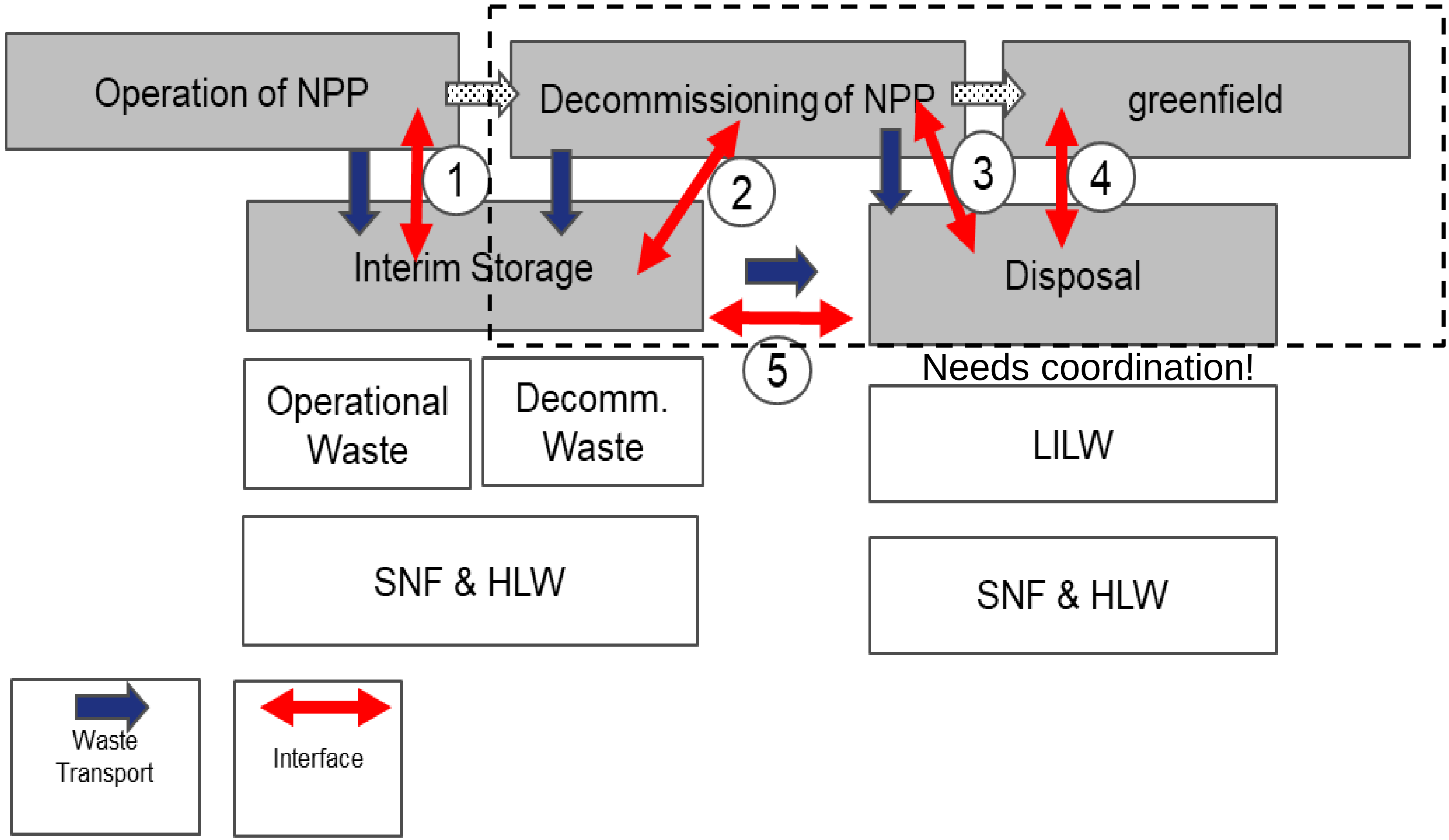
  - Hitachi has never exported a reactor and its recent technology the ABWR has been proven as unreliable (Thomas, 2017b).

  - 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).

Technical System: Overview



Interfaces Between Value-added Stages Need Coordination



Some Key Findings in the U.S. and Germany

- High cost variance:
  - U.S: US$280/kW (Trojan) to US$1,500/kW (Connecticut Yankee)
  - DE: Gundremmingen-A (2.2bn € or 9,280€/kW) and Würgassen (1bn or 1,560€/kW. Both are only latest cost estimates.
- Financing:
  - U.S.: External segregated fund (Nuclear Decommissioning Trust Fund): USD 64 billion in 2016.
  - DE: Internal non-segregated funds: EUR 19.7 billion
- Production:
  - In both countries, the utilities are responsible for decommissioning.
    - DE: competitive tendering of highly specialized works in the hot-zone.
    - U.S: a new organizational model is emerging.

Germany	2015	May 2018
"Warm-up-stage"	10	10
of which defueled	*0*	*1*
"Hot-zone-stage"	3	4
"Ease-off-stage"	9	8
LTE	2	2
Finished	4	5
of which greenfield	*3*	*3*
Shut-down reactors	**28**	**29**

United States of America	May 2018
"Warm-up-stage"	4
of which defueled	*1*
"Hot-zone-stage"	0
"Ease-off-stage"	5
LTE	12
Finished	13
of which greenfield	*6*
Shut-down reactors	**34**

Chapter 5: Nuclear Power Reactor Decommissioning

Research Question / Objectives:

- What is the status quo of decommissioning worldwide?
- What are the organizational models for production and financing of the decommissioning process?
- What are the production costs?

Main Findings:

- Experience in decommissioning a large-scale 1 GW reactor with 40 years of operation is non-existent.
- High cost variance:
  - U.S: US$280/kW (Trojan) to US$1,500/kW (Connecticut Yankee) .
  - DE: 1,560€/kW (Würgassen) to 9,280€/kW (Gundremmingen-A). Both are only latest cost estimates.
- This leads to underestimation of costs and hence increases funding risks.
- Coordination needs at the various interfaces, especially between public and private "duties"
- The decommissioning of the oldest reactors has in most cases not even started and faces particular technical, organizational, and financial challenges (e.g. GCRs).

In Europe (excluding Russia and Slovakia) more than ca 60,500 tons of SNF are stored - 81% of the SNF is wet storage.

Country	SNF inventory [tons]	Fuel Assemblies*	Wet Storage [tons]	SNF in wet storage [%]
BELGIUM	501**	4,173	237	47%
BULGARIA	876	4,383	788	90%
CZECH REPUBLIC	1,828	11,619	654	36%
FINLAND	2,095	13,887	2,095	100%
FRANCE	13,990	n.a.	13,990	100%
GERMANY	8,485	n.a.	3,609	43%
HUNGARY	1,261	10,507	216	17%
LITHUANIA	2,210	19,731	1,417	64%
THE NETHERLANDS	80***	266	80	100%
ROMANIA	2,867	151,686	1,297	45%
SLOVENIA	350	884	350	100%
SPAIN	4,975	15,082	4,400	91%
SWEDEN	6,758	34,204	6,758	100%
SWITZERLAND	1,377	6,474	831	60%
UKRAINE*	4,651****	27,325	4,081	94%
UNITED KINGDOM	7,700	n.a.	7,700	100%
TOTAL	**ca. 60,500**		**ca. 49,000**	**81%**

Notes: * SNF inventory calculations vary by weight per assembly assumptions: Belgium and Hungary assume 120 kg per assembly; Lithuania 112kg, Slovakia 119kg, and Romania 18.1 kg (Romania lists fuel assemblies in units of CANDU bundles). ** 2011 data (Belgium has not published more recent data). *** 2010 data (the Netherlands has not published more recent data). **** 2008 data (the Ukraine has not published more recent data).

Global Trends in Investing in Nuclear Power Plants

In March 2020, the IAEA PRIS database lists

- **20 countries, that are constructing nuclear power plants**
- **53 reactors under construction (56 GW), this represents ~ 14% of total capacity in operation (390 GW)**
- **10 alone in China**
- **Vogtle: first construction start since 1978**
- **Europe: Gen II Civeaux-II (commercial operations in 2002)**
- **Hinley Point C: first construction start since 1980**

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.

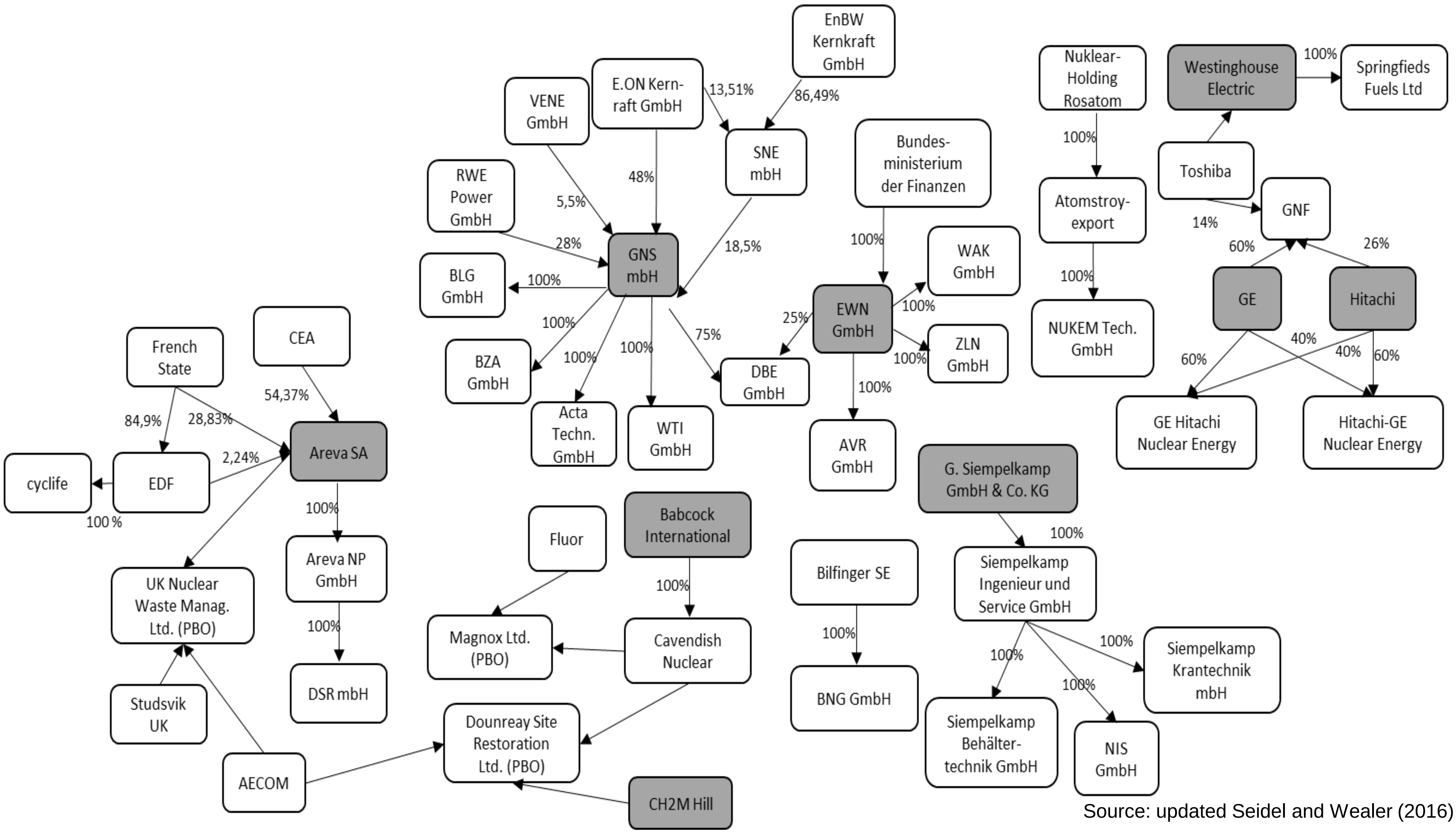
The costs for the legacy fleet have increased steadily and doubled since 2001, when they were estimated to be around €3.3 billion.

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 <u>more time</u>, that <u>the technical feasibility is not fully assured</u>, and that the process <u>will cost overall much more</u> than EDF anticipates.

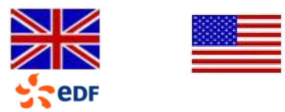
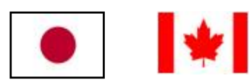
EDF’s new strategy aims to release the GCRs from regulatory control only by the beginning of the 22nd century.

Only a few and highly interconnected specialized decommissioning and RAW companies



Source: updated Seidel and Wealer (2016)

Organizational models for decommissioning in the Case Studies

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

Source: Seidel and Wealer (2016), based on Klatt (2011)

Organization Model United Kingdom

Production:
- NDA tenders decommissioning work in long-term contracts (public procurement)
- RWM Limited (NDA subsidiary) plans and builds
- LLW dipsosal facilities tendered to private companies (Studsvik UK and Areva)
- There is the possibility that the decommission responsibility is transferred to the NDA from the EDF Energy

Financing :
- Legacy fleet paid by public budget
- EDF Energy pays into the Nuclear Liability Funds, owned by the Nuclear Trust (public)
- If EDF Energy wants to receive payments from the fund to meet liabilities it can only be made by application
- NDA acts as an agent

Production / Financing	A) Public enterprise	B) Private enterprise (central or decentralized)	C) Public tender (centralized or decentralized)	D) Further alternatives
1) Public budget	Sellafield Ltd; Magnox		Magnox	
2) External segregated fund	EDF Energy	EDF Energy; Takeover option by the NDA		
3) Internal segregated fund				
4) Internal non segregated fund				
5) Further alternatives				

Decommissioning in the United Kingdom: Competitive Tendering Failed

- Idea: Open the management of the SLCs to competition. These contracts were thought to be competitively tendered under EU public procurement law. The winner of acted as the Parent Body Organization (PBO). The PBO received the shares of the SLC, and organized the strategic management. The idea of opening up the work to private contractors was thought to increase the efficiency of the decommissioning process (MacKerron 2015).

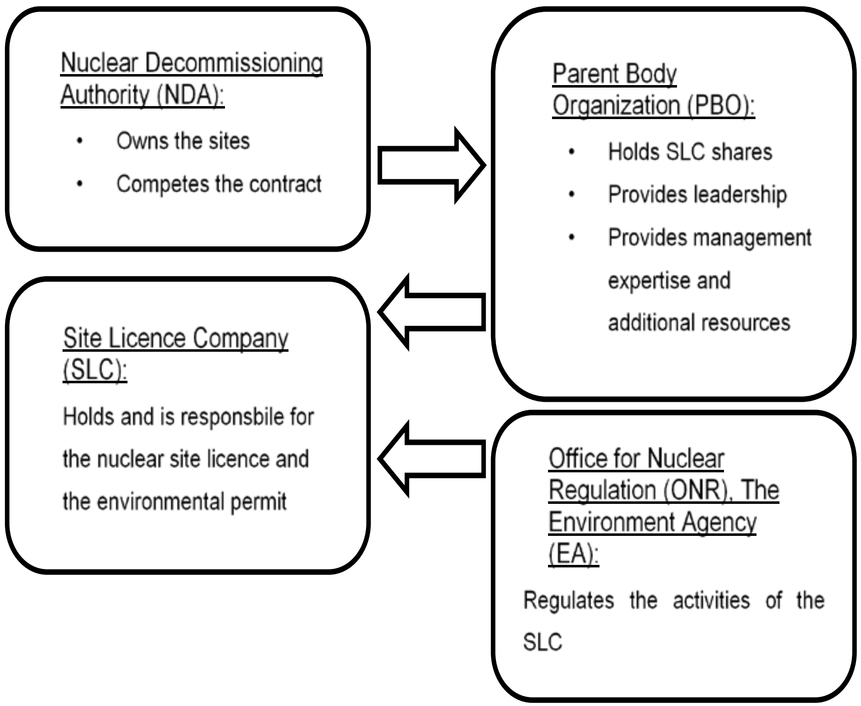
- Since 2016, SLC Sellafield Ltd wholly owned subsidiary of the NDA.

- Complex technical uncertainties at the site are less suitable for the competitive PBO model.
- Decommissioning is expected to extend well into the 22nd century, which requires long-term planning and not changing the strategic management every five years.

- Since 2018, Magnox Ltd. became a subsidiary of the NDA, too.
- The House of Commons found that the NDA had completely failed in both procurement and management of the contract.

- The report concluded, that i.a. the procurement procedure was too complex and that the contract was awarded to the wrong bidder, which resulted in GBP 100 million in settlement of disputes. In addition, the amount of work was drastically underestimated.

Source: Authors


Nuclear Decommissioning Authority (NDA):
• Owns the sites
• Competes the contract
Parent Body Organization (PBO):
• Holds SLC shares
• Provides leadership
• Provides management expertise and additional resources
Site Licence Company (SLC):
Holds and is responsbile for the nuclear site licence and the environmental permit
Office for Nuclear Regulation (ONR), The Environment Agency (EA):
Regulates the activities of the SLC

Organization Model for Germany after the reform recommended by EK and KfK

Production:

- Decommissioning:
  - Stage 3 mostly tendered to specialized companies or deferred strategy applied
- Radioactive Waste Management:
  - Interim storage facilites now owned and operated by the public company BGZ
  - Construction, licensing, and operation of the geological facilities was the scope of the government (BfS, now responsibility of public company BGE

Financing :

- Decommissioning
  - Estimated costs for 23 NPPs 830€/kW (19.719 bn €)
  - Cost increases between 2.9% and 6% (1,400-10,000 €/kW)
- Radioactive Waste Management:
  - Installation of a new external fund (**KfK**) with a sum of around 23 billion Euro including a risk premium
  - All disposal related risks will be the in the responsibility of the public fund – infringes the polluter pays principle
  - Concerns: amount is not high enough to bear all future costs

Production / Financing	A) Public enterprise	B) Private enterprise (decentral or decentralized)	C) Public tender (centralized or decentralized)	D) Further alternatives
1) Public budget	EWN			
2) External segregated fund				
3) Internal segregated fund	KFK			
4) Internal non segregated fund				
5) Further alternatives		E K		

Decommissioning Costs – Experiences and Estimates

Data on actual decommissioning costs are scarce, with only three countries having completed decommissioning projects to full dismantling.

In the US, where the most reactors were completely decommissioned (13 of 34 closed nuclear power plants as of mid-2018) decommissioning costs show a high variance, from US$280/kW to US$1,500/kW.

In Germany, only two commercial reactors have finished decommissioning: Gundremmingen-A was completed after 23 years of dismantling work with a latest estimate of around €2.2 billion in 2013 (US$2.5 billion) or €9,300/kW (US$10,500/kW). At Würgassen, decommissioning costs were around €1.1 billion (US$1.2 billion) or €1,700/kW (US$1,900/kW).

All German decommissioning projects experienced cost increases up to six percent per year, which were much higher than the general inflation rate and the assumed nuclear-specific inflation rate. Despite the cost increases, the estimated costs for future decommissioning (without casks, transport etc.) of around €19.7 billion (US$22.2 billion) or €830/kW (US$940/kW) are still based on the above mentioned and not publically available cost models.

Overview of Financing Schemes for Decommissioning

The polluter-pays-principle is applied to decommissioning in most nuclear countries. However, there are some cases where the state takes over the liability for decommissioning (for example, for the former East German reactors and the Nuclear Decommissioning Authority in the UK).

	Czech Republic	**France (EDF)**	**Germany**
Funding system	Internal segregated and restricted fund	Internal segregated and restricted fund	Internal non-segregated and unrestricted
Controlled by	Operators	Operator	Operators
Accumulated by	Fee on generated electricity	Levy on electricity price	Provisions by operators
Cost estimates	Temelín: US$847 million Dukovany: US$1 billion US$410/kW to US$530/kW	US$35.7 billion for entire fleet US$450/kW for operational; US$1,350/kW for legacy	US$22.2 billion for 23 commercial reactors US$940/kW
Set aside funds, (in % of cost estimate)	Temelín: US$129 million (15%) Dukovany: US$276 million (28%)	US$20.8 billion or 58%	US$26.7 billion*

Source: The World Nuclear Waste Report (2019)

* in 2017, including provisions for casks, transport, and conditioning (also of operational waste).

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