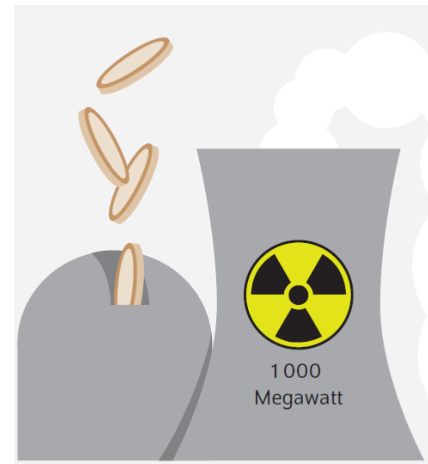
Nuclear Energy Conference, 3d of November 2020

Nuclear Power Economics

Source: EDF



Source: DIW

Technische Universität Berlin

DIW BERLIN

Dr. Ben Wealer

Motivation

- **Is it economically meaningful to limit emissions by investing in nuclear power?**

- Conventional business economics analysis always derives the same conclusion: nuclear power plants were never competitive in deregulated markets.
- Nonetheless it still debated intensively in both, industrialized (e.g., MIT 2018) and emerging countries (e.g., Kessides 2014; Roh, Choi, and Chang 2019) if or to what extent nuclear power plays a role in a decarbonized future.
- But as I will argue in this presentation a more holistic approach along the value-added chain of nuclear power is needed;
- especially bringing the issues of decommissioning and waste management to the forefront.

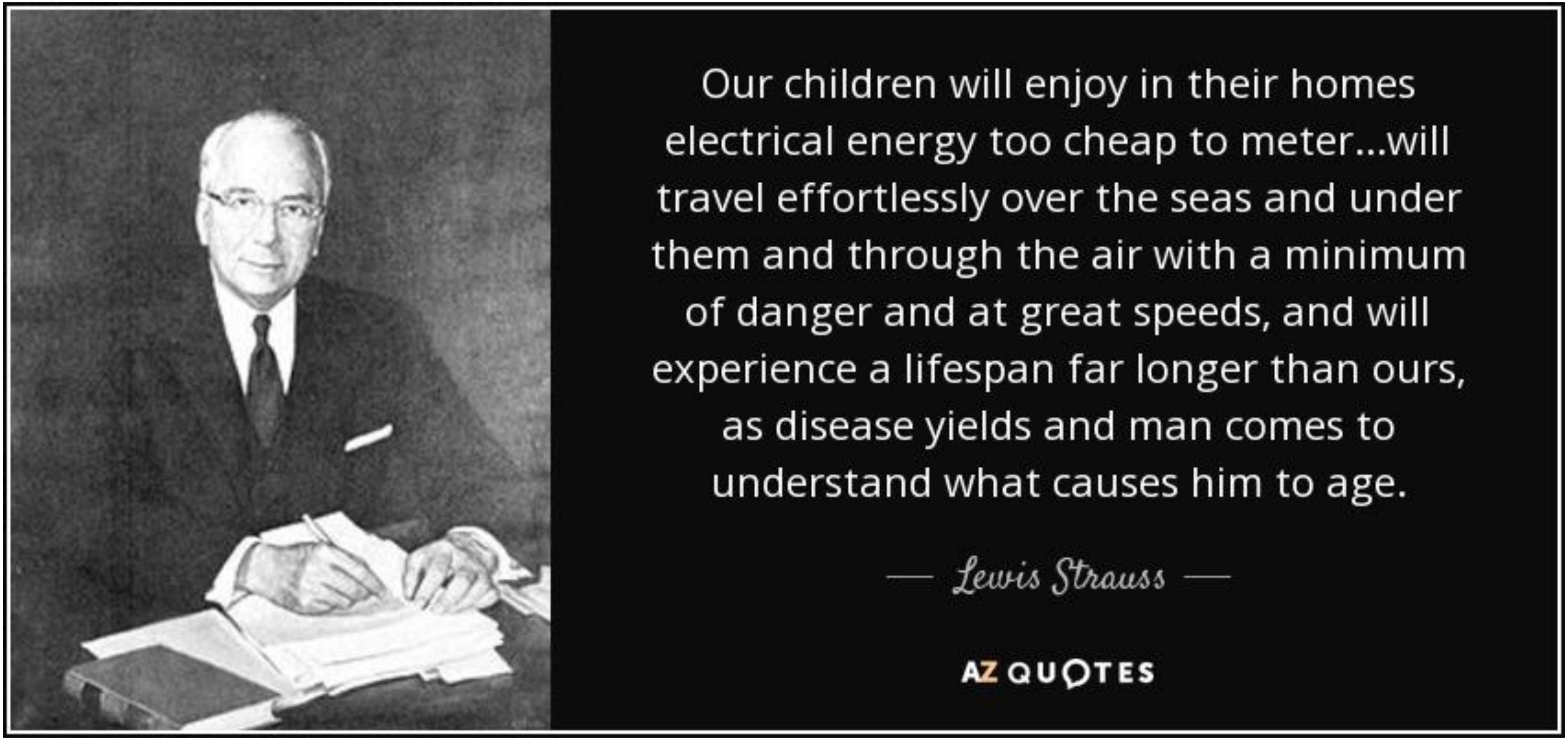
Agenda

1) Looking back…
2) The nuclear power industry
3) Investing into new nuclear power plants
4) The (neglected) issues of decommissioning and nuclear waste
5) Conclusion

Agenda

1) **Looking back…**
2) **The nuclear power industry**
3) **Investing into new nuclear power plants**
4) **The (neglected) issues of decommissioning and nuclear waste**
5) **Conclusion**

The dream (1954) …



The diffusion of nuclear power plants

Research Questions / Objectives:

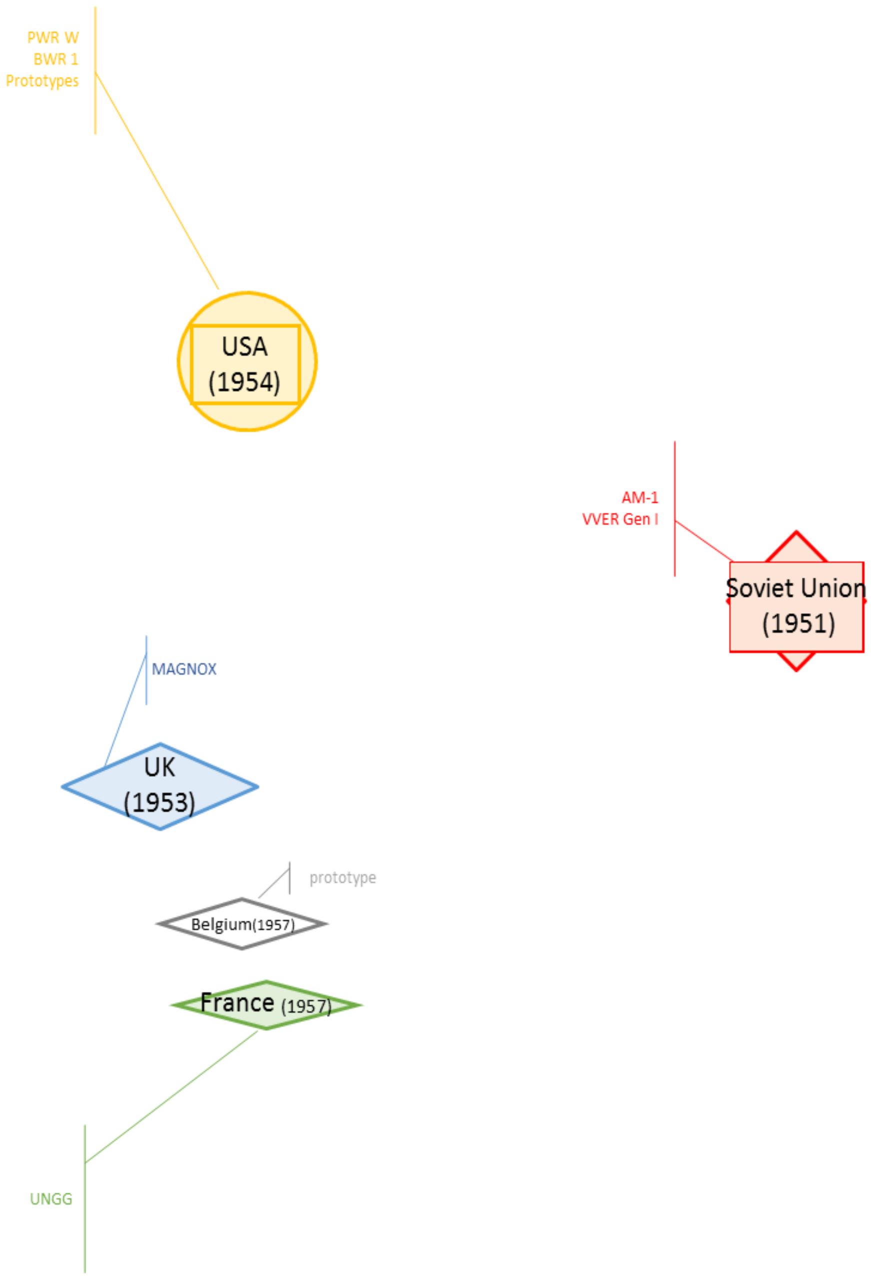
- Tracing the development of nuclear power since its beginnings to allow a better understanding of issues on nuclear power going forward.

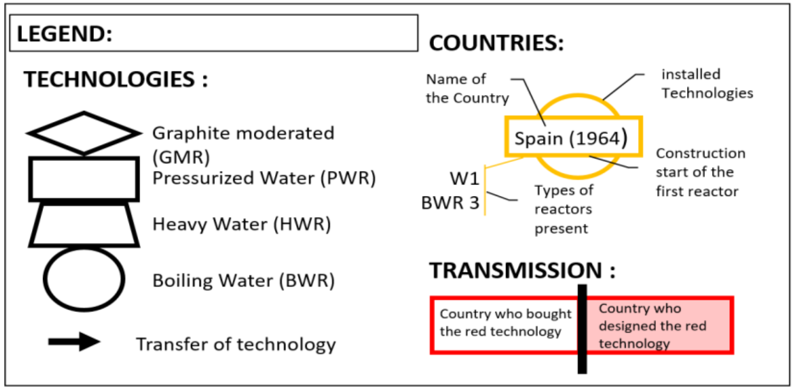
Approach:

- Political economy analysis of, linking the development of reactor technology to political structures and institutional characteristics since its beginnings, by providing both a technological and country-specific analysis.

Period 1, 1945-mid 1950s:

- four major countries had established independent, national pathways of nuclear technologies for military purposes and electricity generation: the U.S., the Soviet Union, the U.K., and France

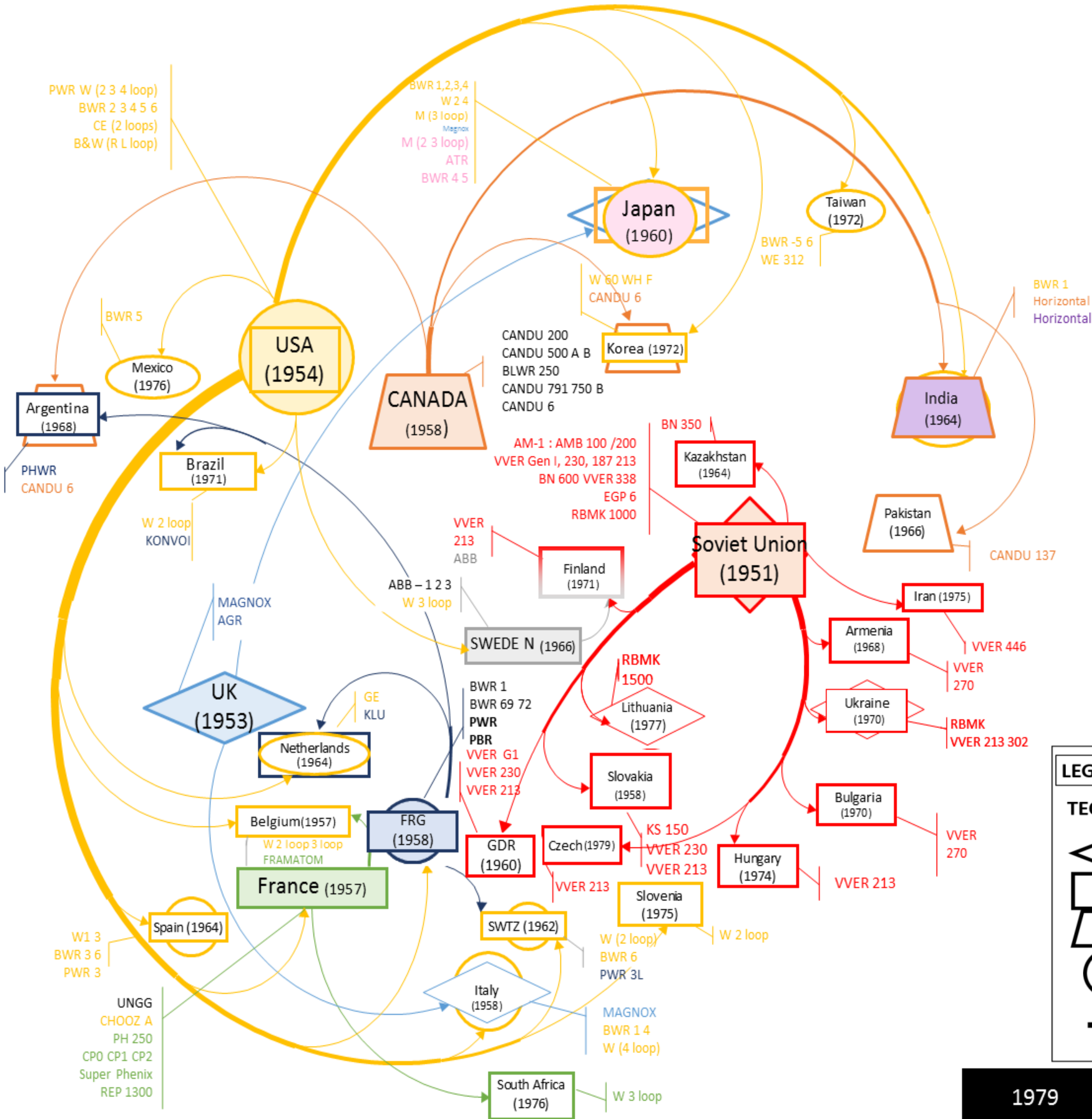


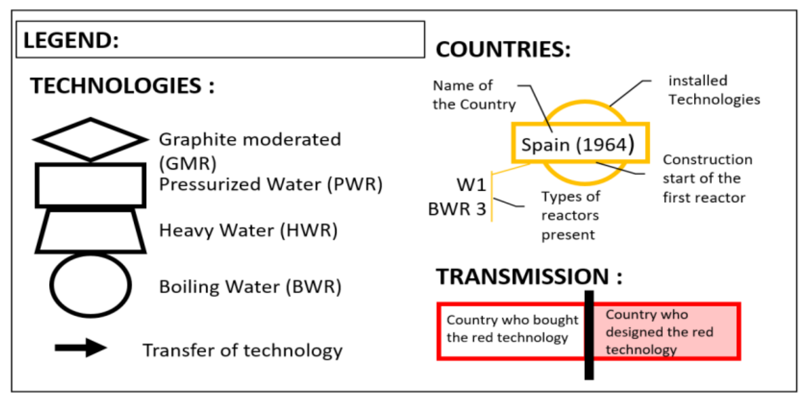


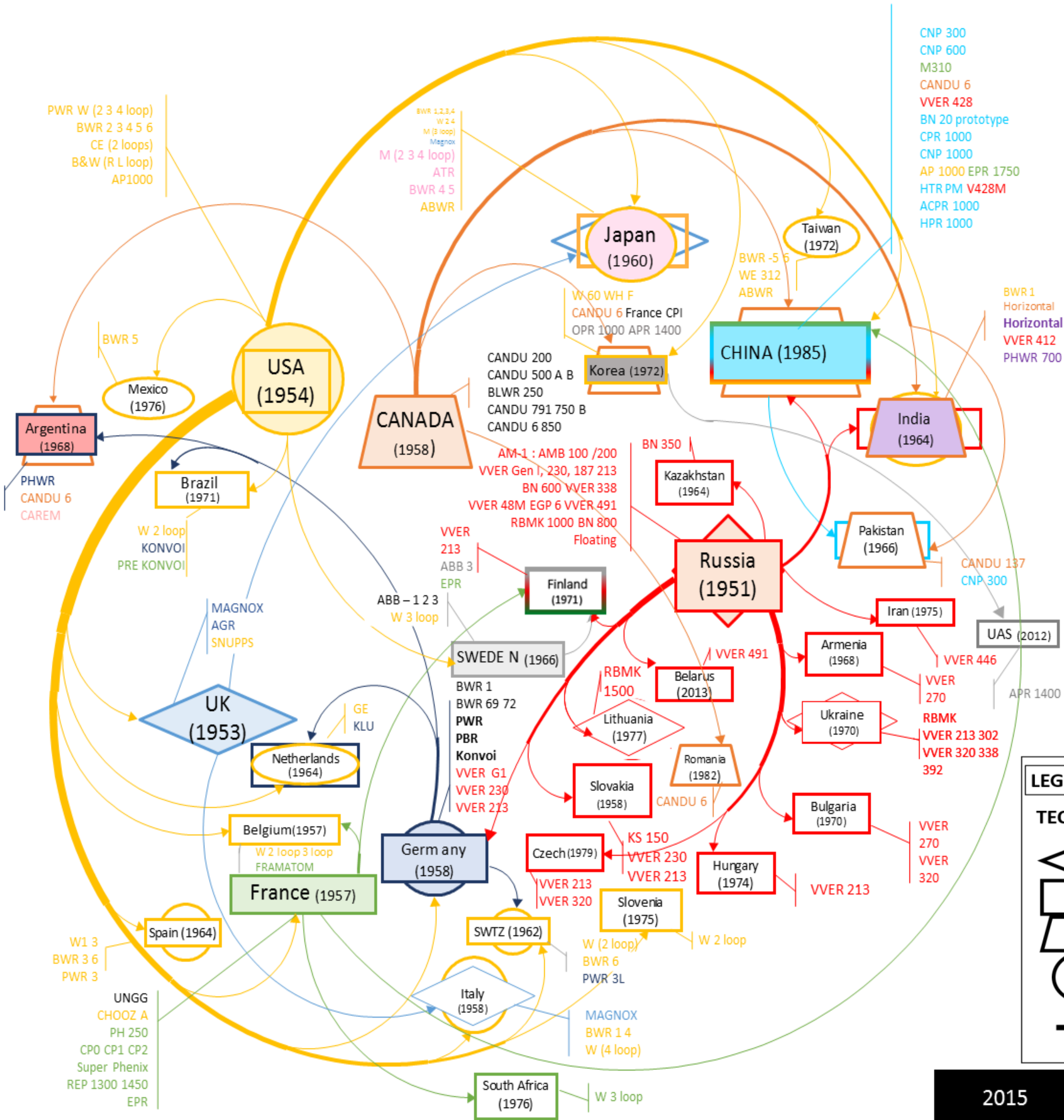
1957

Period 2, mid-1950s – mid-1980s:

- Fierce competition between the two nuclear superpowers.
- US approach was much more “liberal”, by selling technology and licenses to adoption countries,
- whereas the USSR kept the technology and only gave away turnkey reactors to satellite states.
- Some countries were able to develop their own nuclear pathway.





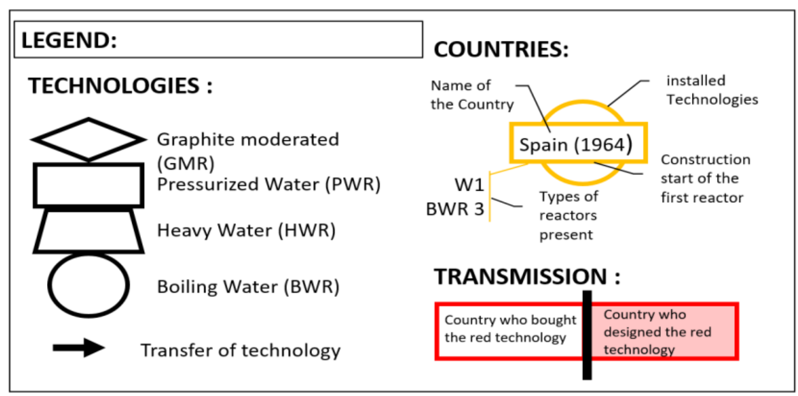


Period 3, mid-1980s- 2011:

- China developed its nuclear sector, to become the third nuclear superpower.

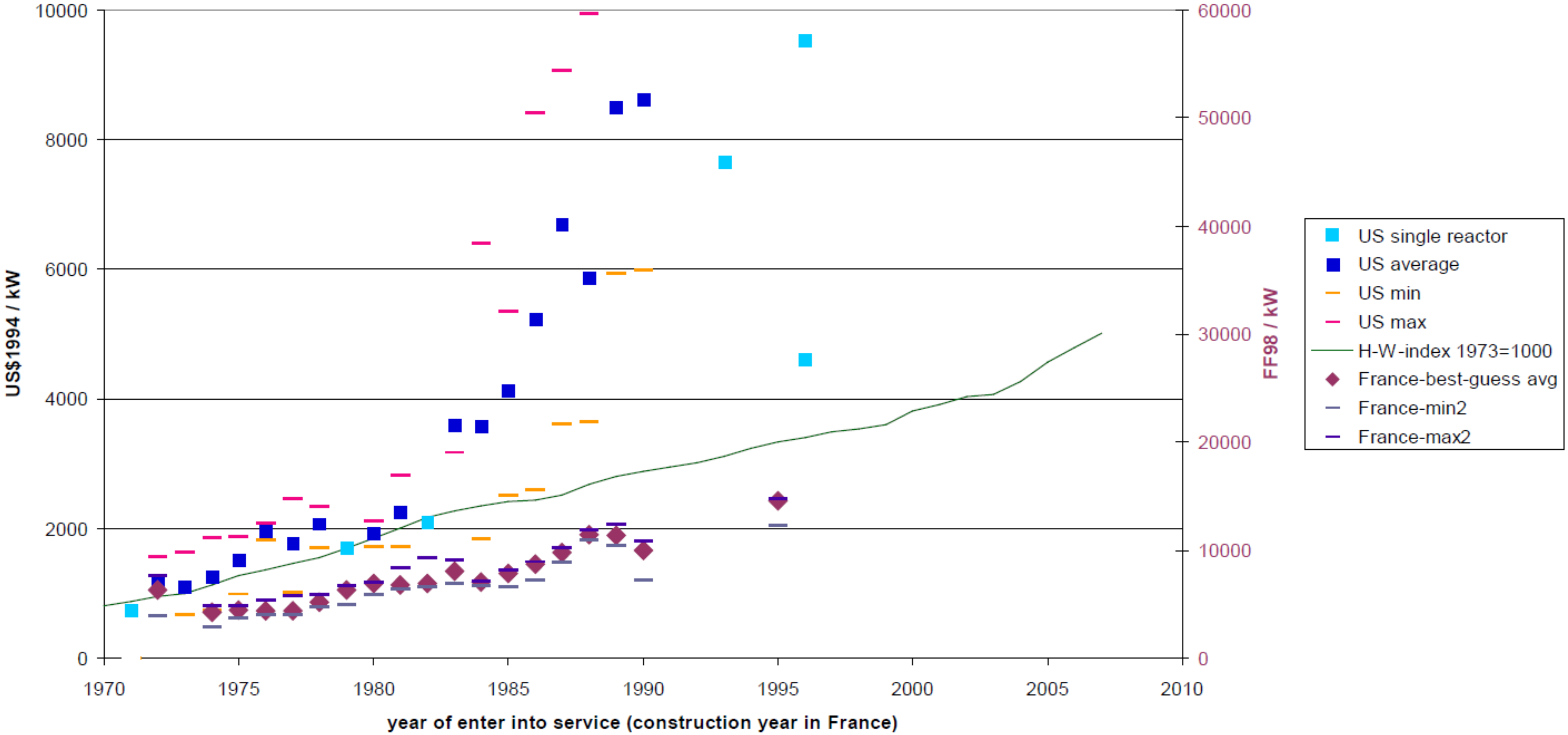
Period 4, post Fukushima:

- characterized by implosion of nuclear power in Western economies (i.e. closure of reactors, abandonment of new build projects).
- This leaves the development of nuclear power to “other”, non-market systems, mainly China and Russia.



2015

Nuclear power plants are historically characterized by high construction costs



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

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

MIT (2003): The Future of Nuclear Power

“In deregulated markets, nuclear power is not now cost competitive with coal and natural gas.” (p. 3)

University of Chicago (2004):

“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.” (p. 5-1)

D’haeseleer (2013): 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)

Davis, L.W. (2012): Prospects for Nuclear Power. Journal of Economic Perspectives (26, 49–66)

“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 diffusion of nuclear power plants

Main Findings:

- The country-by-country analysis reveals different patterns:
  - We distinguish “economies-of-scope” trajectories,
  - recipient countries of nuclear technologies with and without subsequent indigenous technology catch-up,
  - We also identify current trends in potential newcomer countries (e.g. Turkey, Saudi Arabia).
- Period 4: Post Fukushima is characterized by implosion of nuclear power in Western economies (i.e. closure of reactors, abandonment of new build projects).
- This leaves the development of nuclear power to “other”, non-market systems, mainly China and Russia.

Publication:

- Wealer, Ben, Simon Bauer, Nicolas Landry, Hannah Seiß, and Christian von Hirschhausen. 2018. “Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017).” Data Documentation 93. Berlin: DIW Berlin, TU Berlin.
- Wealer, Ben, Simon Bauer, Leonard Göke, Christian von Hirschhausen, and Claudia Kemfert. 2019. “High-Priced and Dangerous: Nuclear Power Is Not an Option for the Climate-Friendly Energy Mix.” DIW Weekly Report 30/2019: 235–243.

Agenda

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5) Conclusion

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).

The System Good Nuclear Power: A Stylized Description

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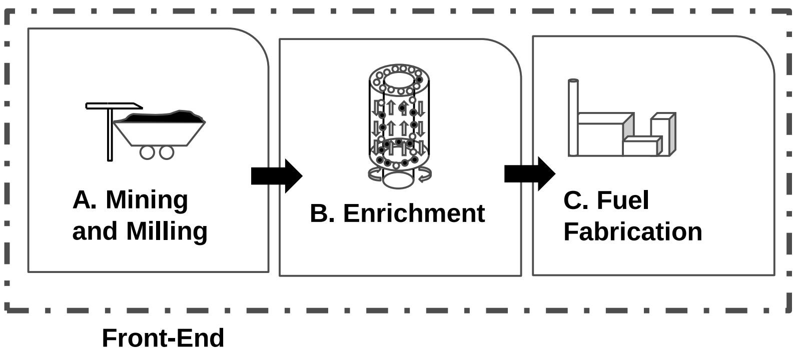

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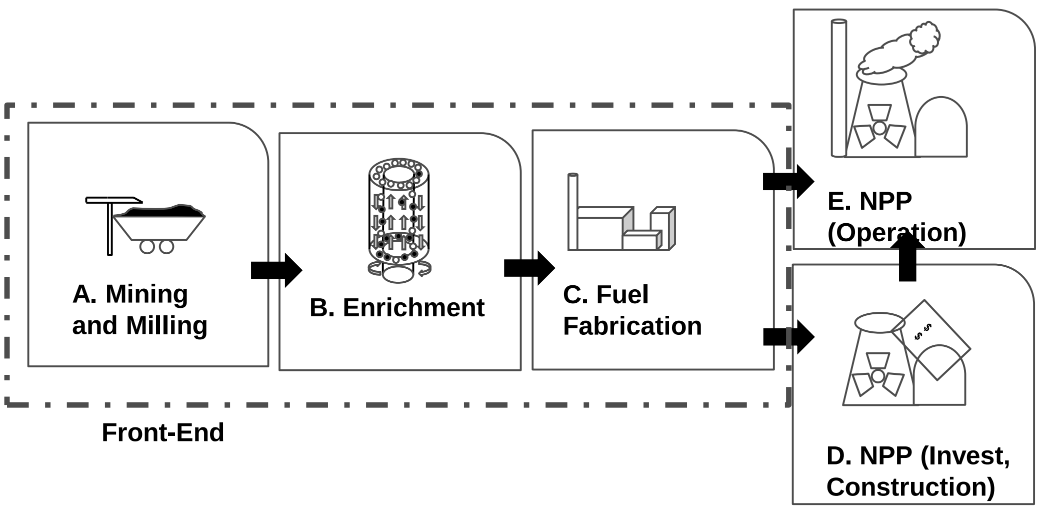

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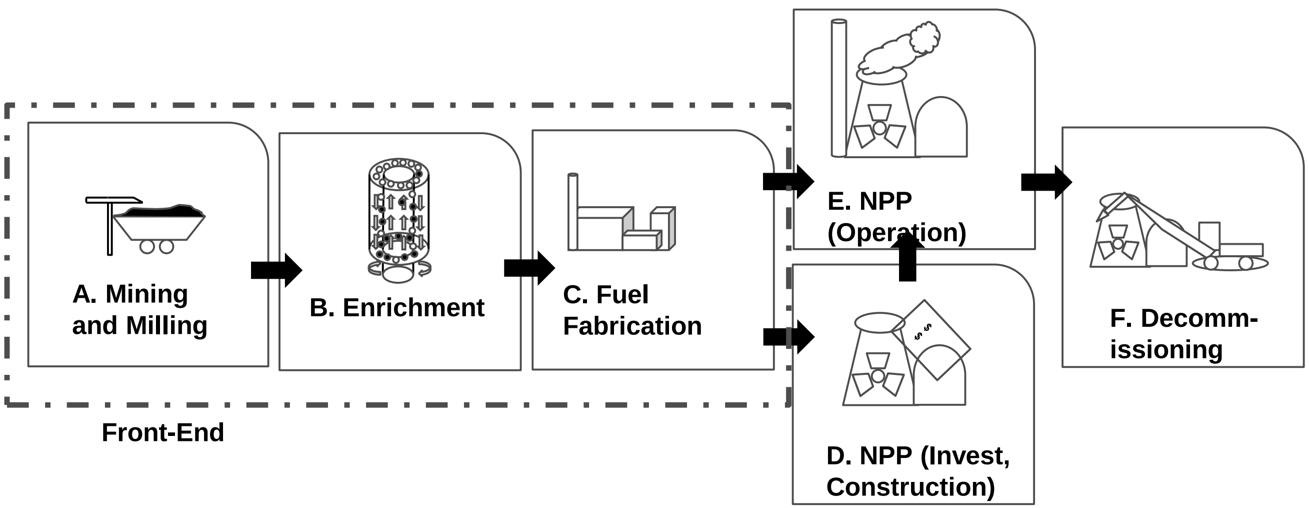
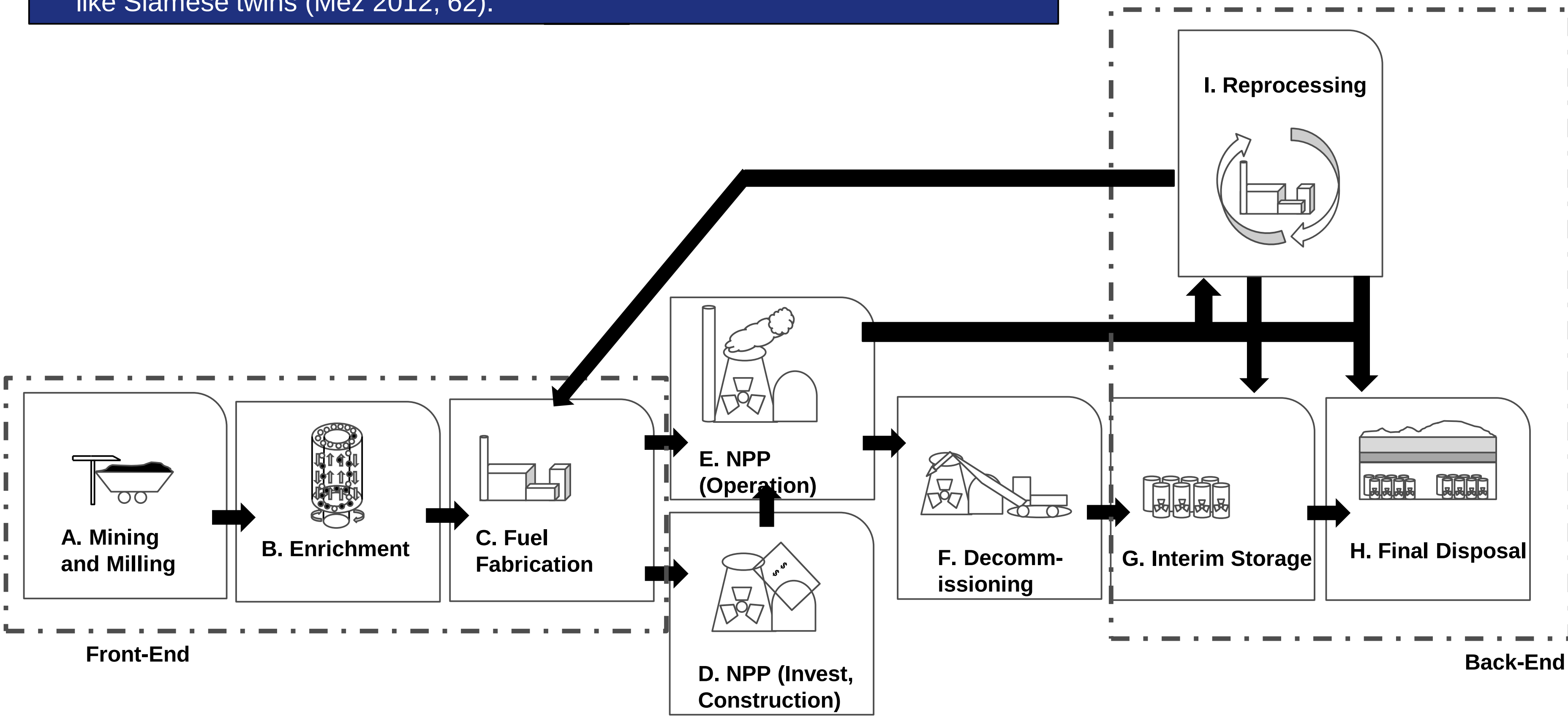


The System Good Nuclear Power: A Stylized Description

- 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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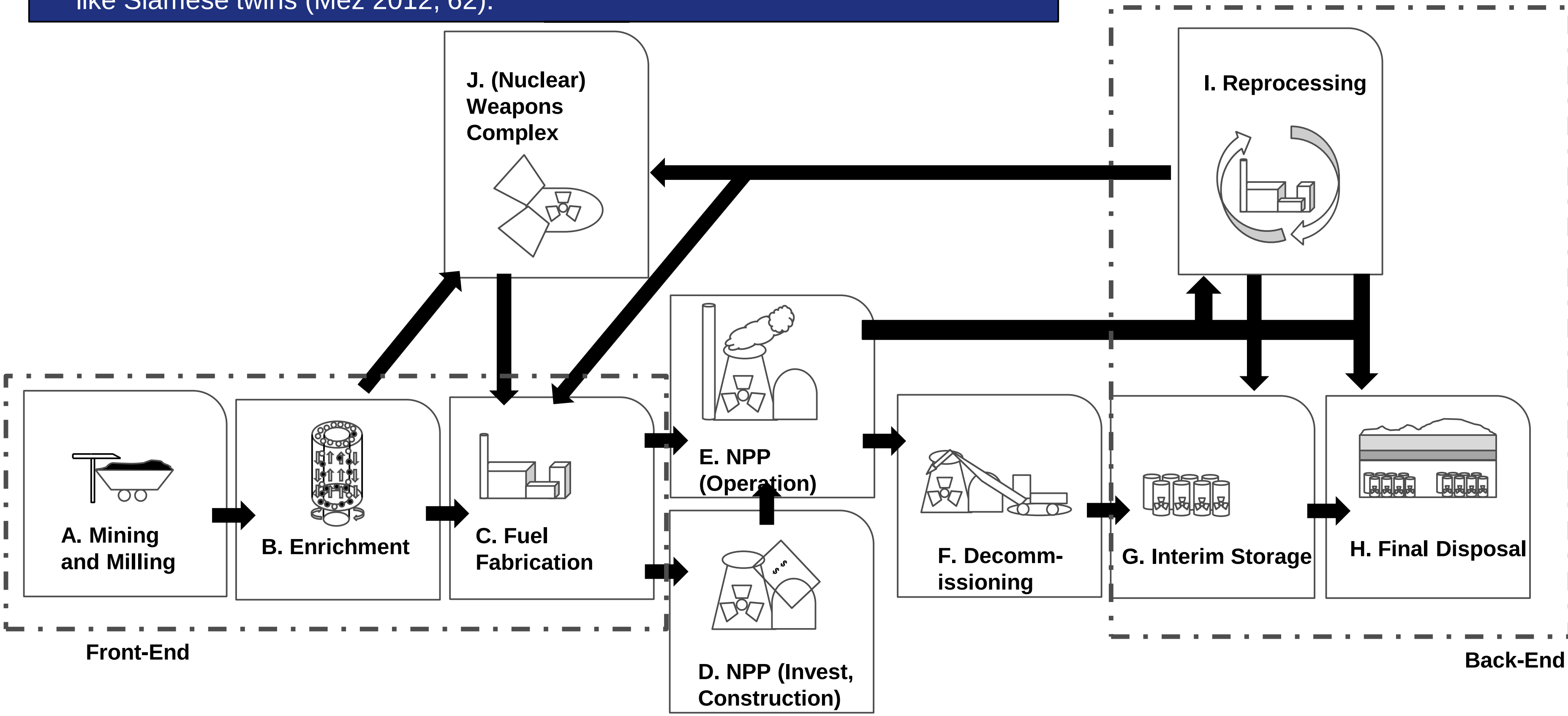

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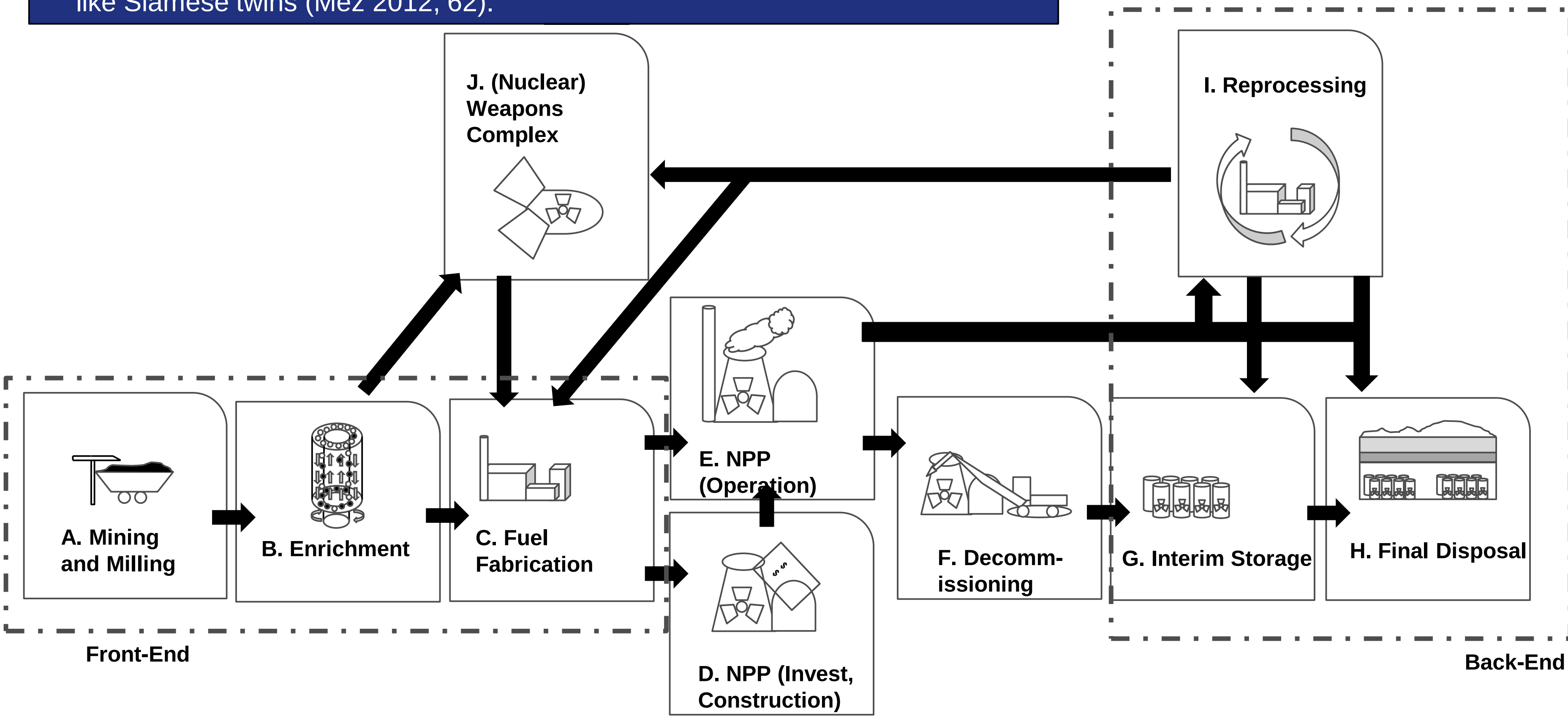
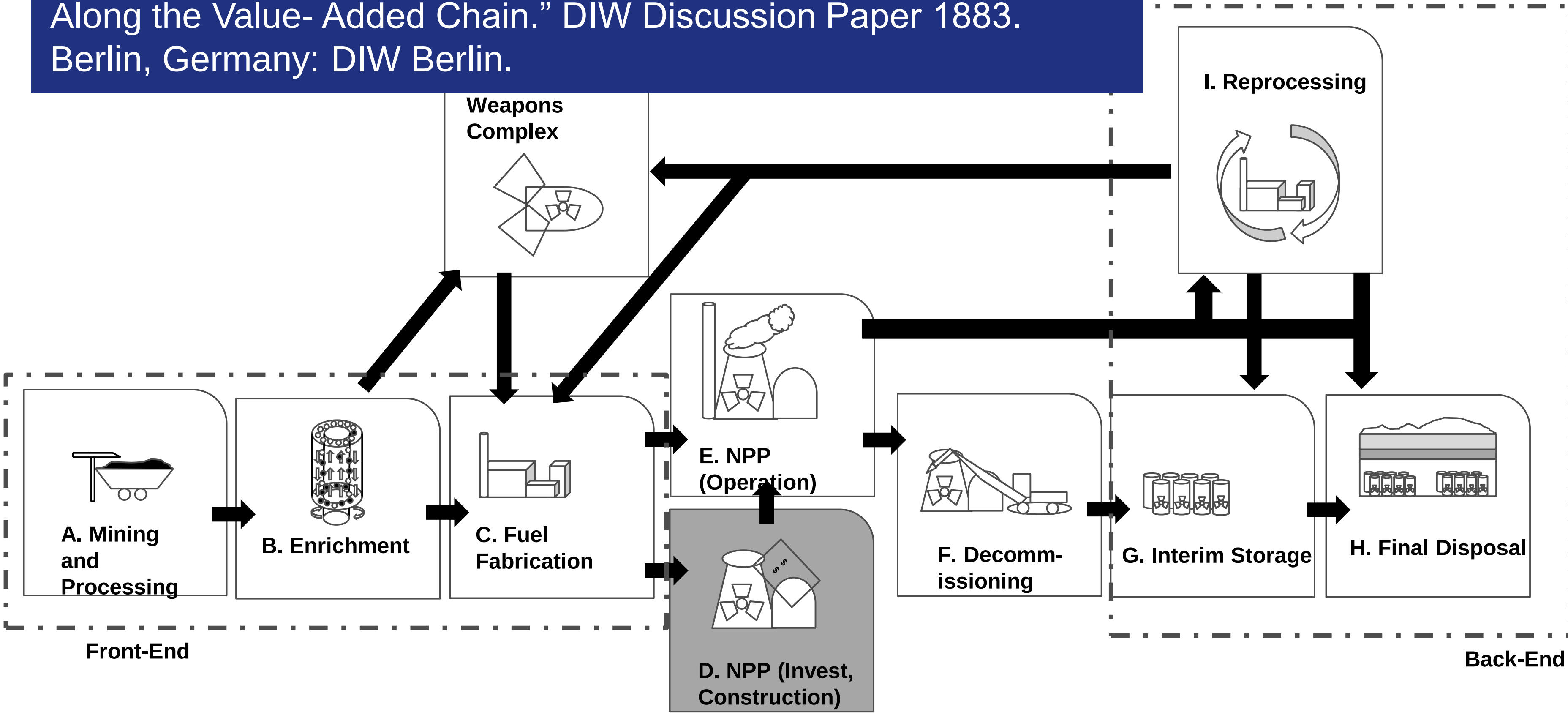
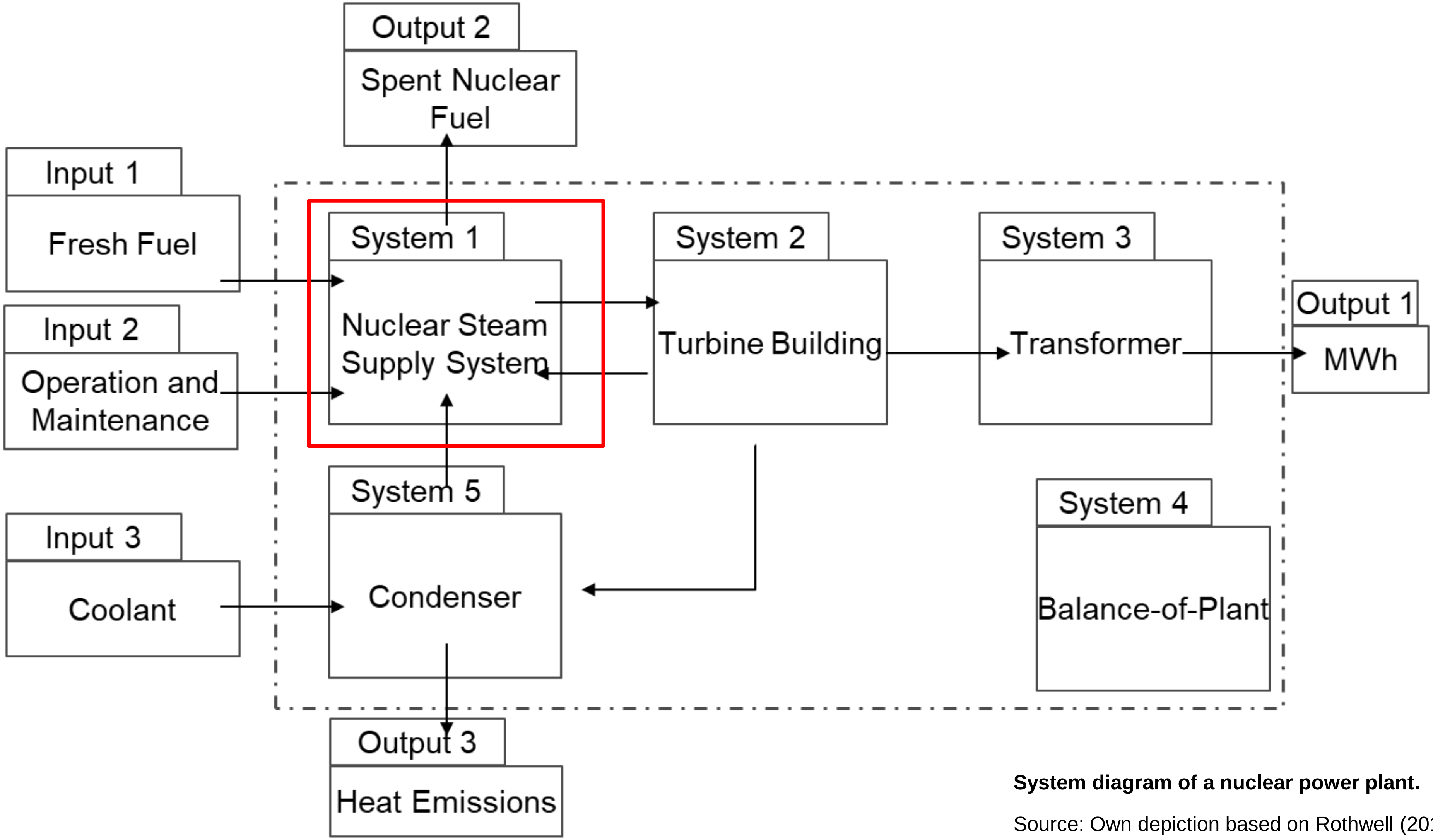


Chapter 4: Economics of Nuclear Power Reactors

Wealer, Ben, and Christian von Hirschhausen. 2020. "Nuclear Power as a System Good. Organizational Models for Production Along the Value- Added Chain." DIW Discussion Paper 1883. Berlin, Germany: DIW Berlin.



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



System diagram of a nuclear power plant.

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

Organizational Models for the Production of NPPs

- **Rosatom strongly dominates the reactor market.**
- **Overall, the market is over-concentrated with a HHI of more than 1,500.**
- **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.
- **The U.S. and Japan are the only two countries where “privately-owned” companies construct reactors.**

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).**

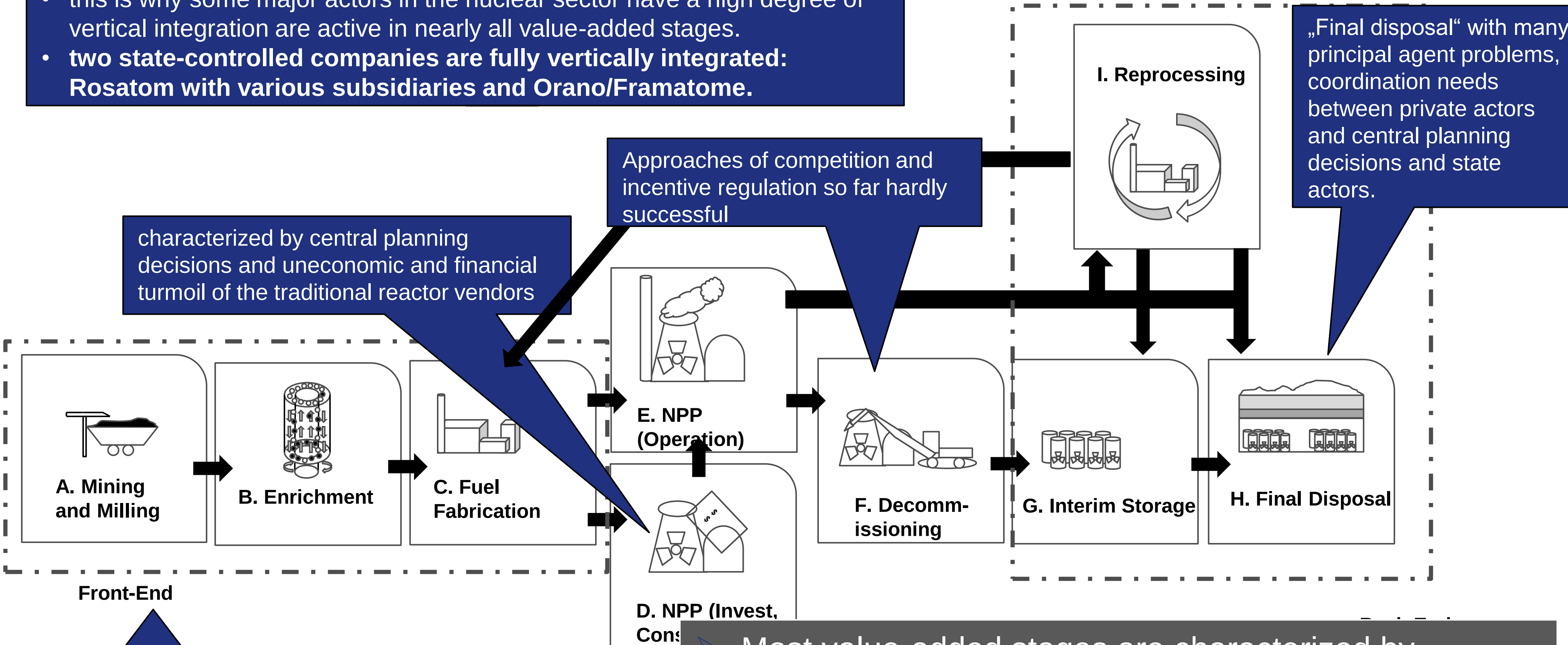
Organizational Models for Provision of NPPs

- **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).

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.**



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).

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Economics of Nuclear Power Reactors

Research Question / Objectives:

- What can a private investor expect when she invests into a third generation nuclear power plant?
- We focus on the perspective of an investor and projects in Western economies and thus exclude non-market institutional contexts from the analysis, where data quality and the levels of subsidies make an economic analysis difficult, such as China or Russia.

Approach:

- Employing a Monte-Carlo simulation technique, which allows to take into account uncertainties on a variety of parameters.

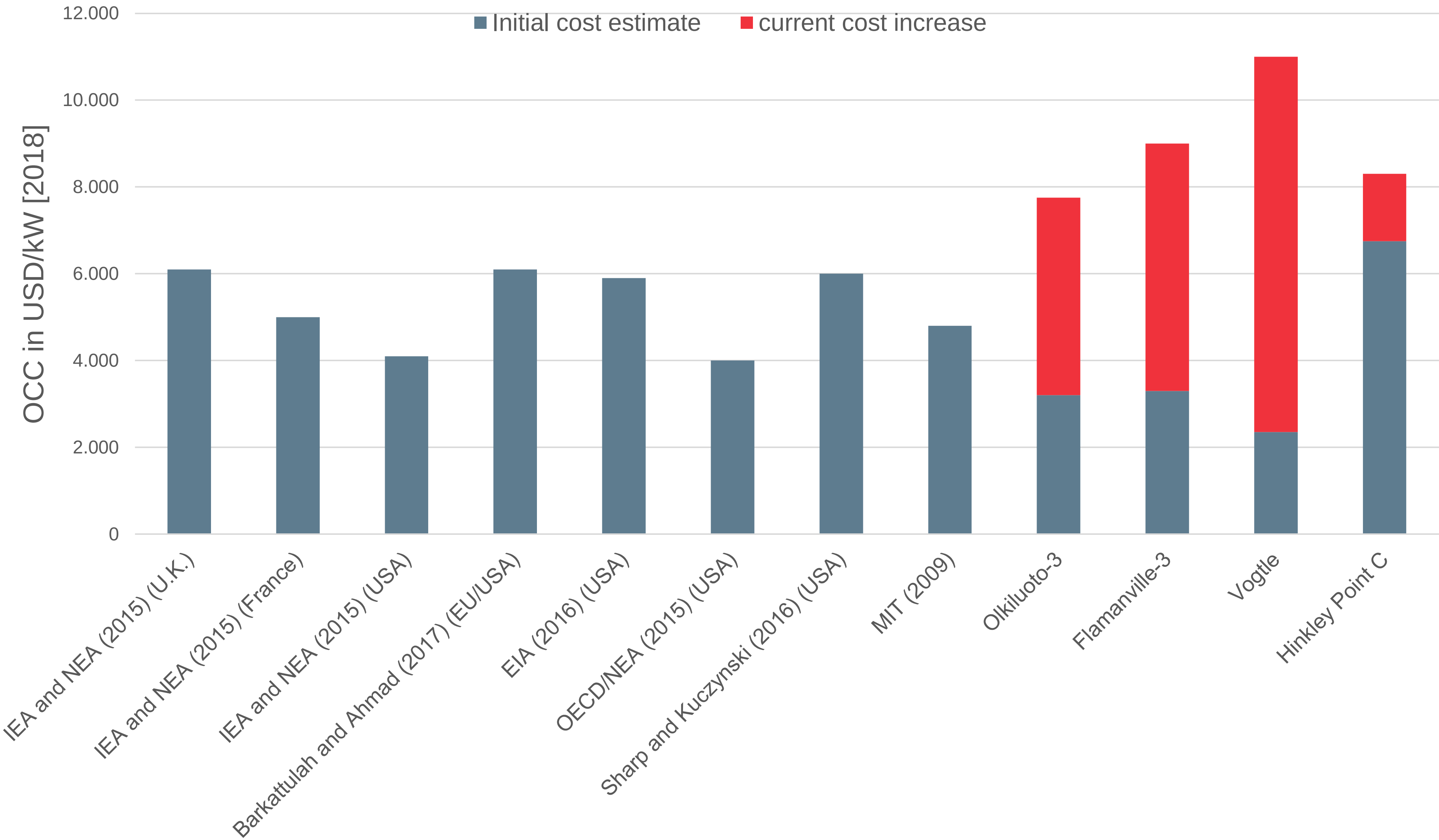
Future investments consist of third generation reactors

- **Only 24 NPPs or 26 GW connected to the grid (~ 7% of operational capacity).**
- **In early 2020: Only China and Russia operate Gen III+ reactors.**
- **Not one third generation reactor was completed in the Western economies.**
- **Initial construction durations of around five years increased at least threefold.**

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.

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



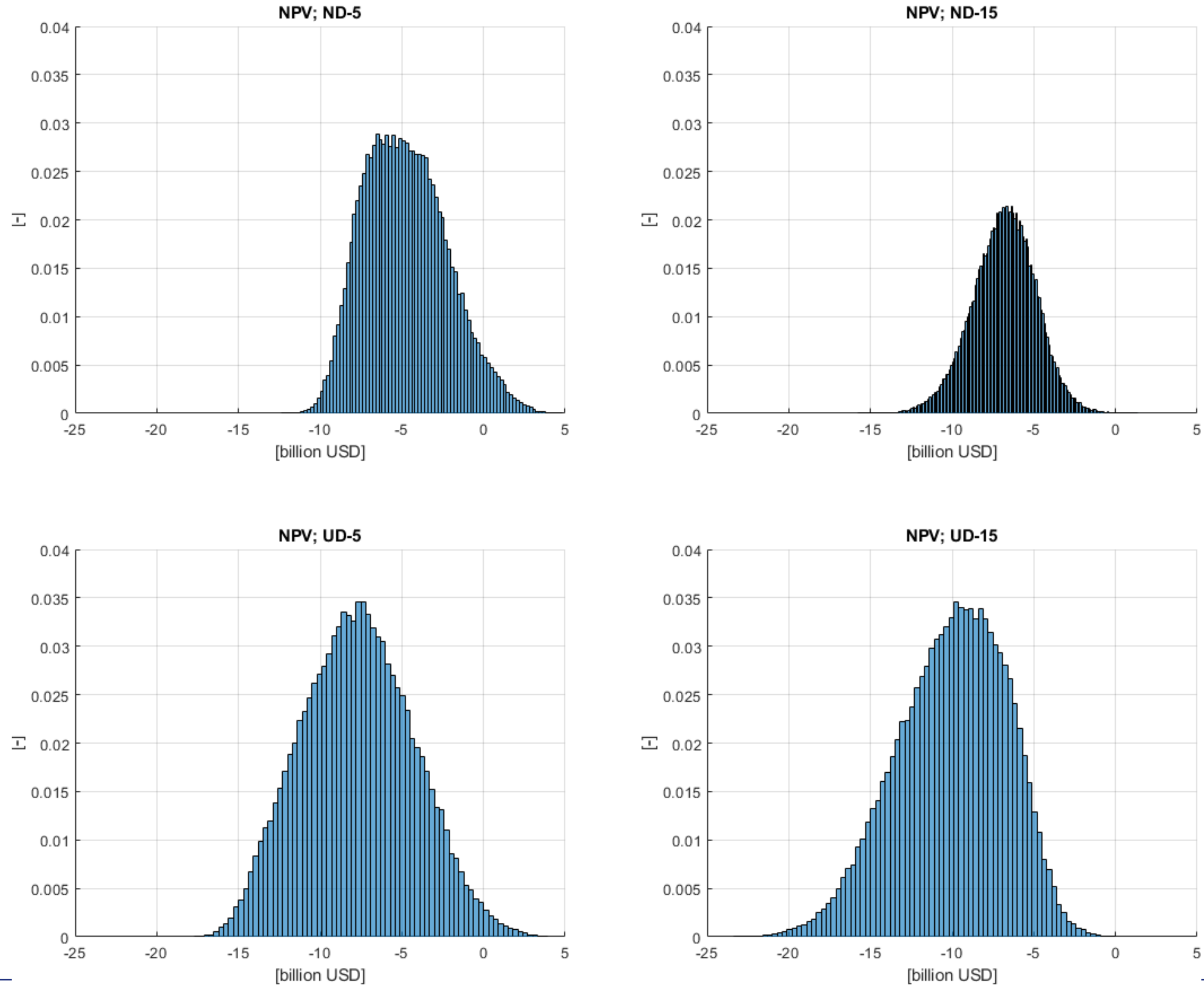
Source: Own depiction

Inputs for the Monte Carlo Simulation

Parameter	Distribution	Range
Overnight construction costs (OCC) [USD/kW]	Uniform / normal	4,000-9,000
Wholesale price of electricity [USD/MWh]	Uniform	20-80
Weighted average cost of capital (WACC) [%]	Uniform	4-10
Fixed O&M [USD/MW]	Constant	93,280
Variable O&M [USD/MWh]	Constant	2.14
Fuel [USD/MWh]	Constant	10.11
Plant construction period T_{con} [years]	Constant	5, 15
Plant operation period [years]	Constant	40
Plant capacity to grid [MW]	Constant	1600
Capacity factor	Constant	0.85
Number of experiments n [-]	-	100,000

[1] Normal density suggested by Rothwell (2016).

Independent of the Distribution of the OCC and the Construction Duration, NPVs are Highly Negative



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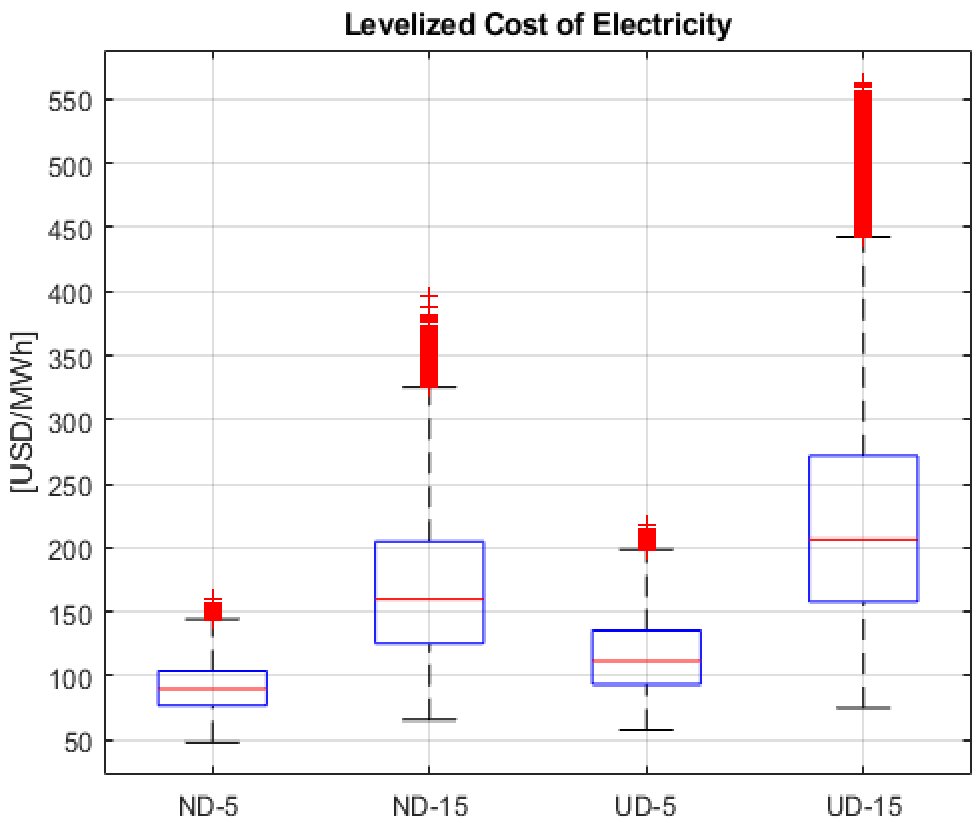
Levelized Cost of Electricity
[USD/MWh]
550
500
450
400
350
300
250
200
150
100
50
ND-5
ND-15
UD-5
UD-15

Investing into third generation nuclear powers plants

Main Findings:

- Even **without accounting for decommissioning and waste management** costs the expected net present values are highly negative in most of the cases, in the range of several billion USD.
- Longer lifetimes made possible by new reactor design is no game changer for profitability.
- The results also confirm the importance of capital costs and the length of the construction period: Interest during construction times is a major cost driver not to be underestimated.

Publication:

- Wealer, Ben, Simon Bauer, Leonard Göke, Christian von Hirschhausen, and Claudia Kemfert. 2019b. "Economics of Nuclear Power Plant Investment - Monte Carlo Simulations of Generation III/III+ Investment Projects." DIW Discussion Paper 1833. Berlin, Germany: DIW Berlin.

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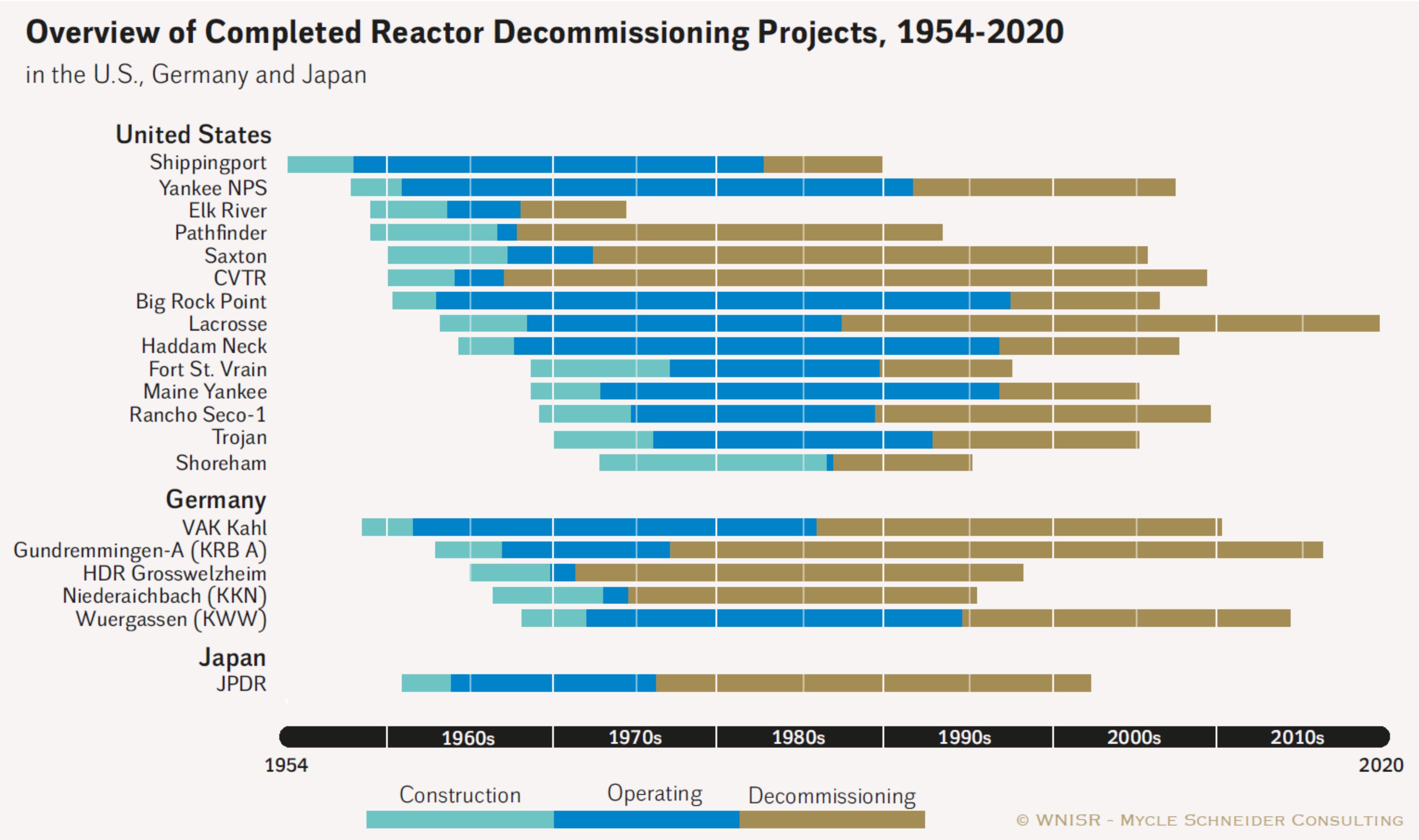
Decommissioning Takes Much Longer Than Expected, In Some Cases Even Longer Than Construction and Operation Combined



Decommissioning costs

- **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.**
- **The decommissioning of the oldest reactors has in most cases not even started and faces particular technical, organizational, and financial challenges (e.g. GCRs).**
- **Czech Republic, the estimates for decommissioning its six VVER reactors are between US$412-532/kW (or around US$1.8 billion).**
- **VVER reactors have not yet been decommissioned anywhere in the world.**
- **The most advanced decommissioning project is Greifswald and Rheinsberg in Germany, where the latest cost estimate is also around €6.5 billion (US$7.3 billion) or €3,090/kW.**

There is not one geological disposal facility in operation worldwide

Country	Waste type	Host rock	Site selection status	Underground Research Laboratory	Construction permit	Time frame to repository license
BELGIUM	SNF, HLW, TRU	clay, unconsolidated	appointed	Hades		not scheduled
CANADA	SNF, HLW, TRU	crystalline	deferred*	none		not scheduled
CHINA	HLW, TRU	crystalline, clay	ongoing?	Beishan		not scheduled
CZECH REPUBLIC	HLW	crystalline	1990-2015 (est.)	none		2065 (est.)
FINLAND	SNF	Crystalline	appointed (1985-2000)	Onkalo RF	2018	2024 (est.)
FRANCE	HLW, TRU	clay, consolidated	appointed	Bure, Tournemire	2020 (est.)	not scheduled
GERMANY	SNF, HLW, TRU	salt, clay, Crystalline	2017-2031 (est.)	none		2050 (est.)
HUNGARY	SNF, TRU	clay	1995-2030 (est.)	Pécs		not scheduled
JAPAN	HLW, TRU	crystalline, sediments	2010-2030 (est.)	Honorobe Mizunami, others		not scheduled
THE NETHERLANDS	SNF, HLW	open	deferred	none		storage >100 years
SPAIN	SNF, HLW	salt, clay, Crystalline	deferred	none		not scheduled
SWEDEN	SNF (HLW)	crystalline	appointed (1980s-2009)	Äspö	ongoing (deposited 2011)	not scheduled
SWITZERLAND	SNF, HLW, TRU	clay, consolidated	2008-2030 (est.)	Mont-Terri		2060 (est.)
UNITED KINGDOM	HLW, TRU	not specified, different UK-country policies	2008	none		not scheduled
USA	TRU-wastes	salt	appointed (1972-1988)	none	repository in operation (1998/2000)	
	SNF, HLW	tuff (other)	deferred	none		not scheduled

Source: Own compilation based on official country reports
Notes: *on voluntary basis. est. = estimated; HLW = high-level waste; SNF = spent nuclear fuel; TRU = transuranic waste

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%**

Source: World Nuclear Waste Report 2019

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).

Agenda

1) Some global trends
2) Demand side or „who is constructing?“
3) Supply side and technological trends
4) The perspectives of nuclear power
5) **Conclusion**

Main findings

- **Economics never played a role in nuclear power diffusion**
- **Nuclear power historically struggled with ever increasing costs. To this day, technological improvements and potential learning effects did not materialize in cost reductions.**
- **Nuclear power is no option for rapid decarbonization due to very long construction times.**
- **The investment into third Gen III reactors results in large losses.**
- **Traditional reactor vendors in financial turmoil, while China and foremost Russia have become the major suppliers.**
- **Looking ahead: Attention should be paid to the unresolved issues of decommissioning and waste management.**

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Thank you for your attention!

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TABLE 6: Funding systems for decommissioning in the Czech Republic, France, and Germany as of December 2018

	CZECH REPUBLIC	FRANCE*	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 (58%)	US$ 26.7 billion*** (n.a.)

Source: Own depiction.
Notes: * only applies to EDF
** excluding costs for casks, transport, and conditioning
*** including provisions for casks, transport, and conditioning (also of operational waste); in 2017

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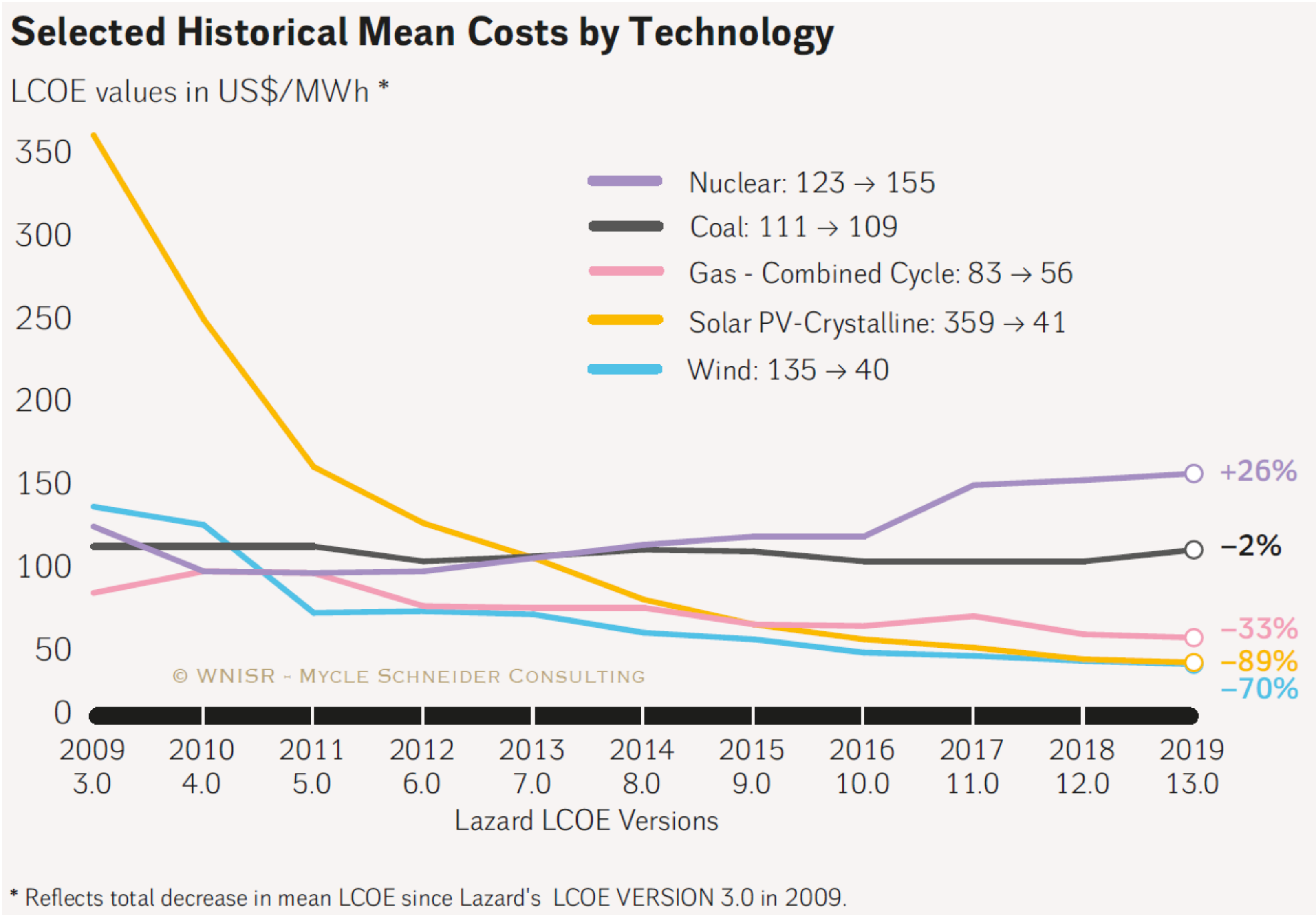
Selected Historical Mean Costs by Technology
LCOE values in US$/MWh *
350
300
250
200
150
100
50
0
Nuclear: 123 → 155
Coal: 111 → 109
Gas - Combined Cycle: 83 → 56
Solar PV-Crystalline: 359 → 41
Wind: 135 → 40
+26%
−2%
−33%
−89%
−70%
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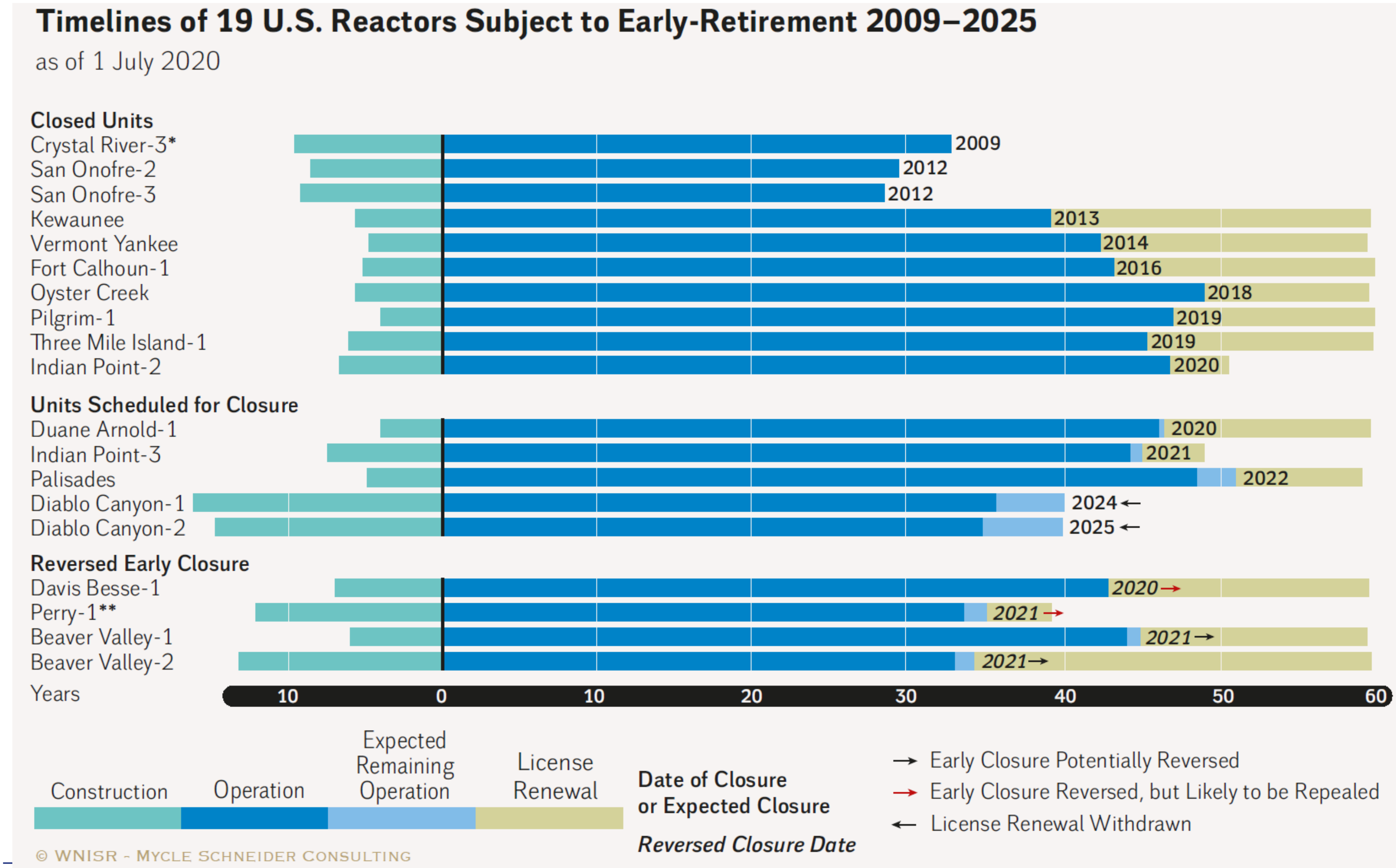
2009 3.0
2010 4.0
2011 5.0
2012 6.0
2013 7.0
2014 8.0
2015 9.0
2016 10.0
2017 11.0
2018 12.0
2019 13.0
Lazard LCOE Versions
* Reflects total decrease in mean LCOE since Lazard's LCOE VERSION 3.0 in 2009.

Back-up



Timelines of 19 U.S. Reactors Subject to Early-Retirement 2009–2025
as of 1 July 2020
Closed Units
Crystal River-3*
2009
San Onofre-2
2012
San Onofre-3
2012
Kewaunee
2013
Vermont Yankee
2014
Fort Calhoun-1
2016
Oyster Creek
2018
Pilgrim-1
2019
Three Mile Island-1
2019
Indian Point-2
2020
Units Scheduled for Closure
Duane Arnold-1
2020
Indian Point-3
2021
Palisades
2022
Diablo Canyon-1
2024 ←
Diablo Canyon-2
2025 ←
Reversed Early Closure
Davis Besse-1
2020 →
Perry-1**
2021 →
Beaver Valley-1
2021 →
Beaver Valley-2
2021 →
Years
10
0
10
20
30
40
50
60
Construction
Operation
Expected Remaining Operation
License Renewal
Date of Closure or Expected Closure
Reversed Closure Date
→ Early Closure Potentially Reversed
→ Early Closure Reversed, but Likely to be Repealed
← License Renewal Withdrawn
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