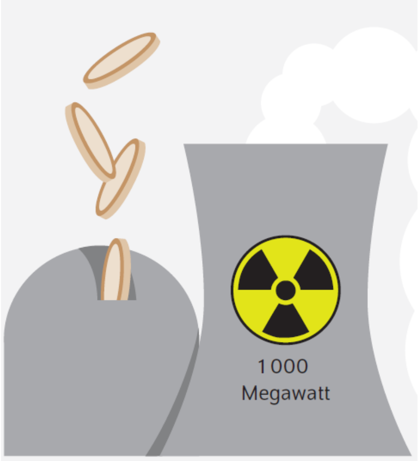
Critically examining nuclear as a (false) climate solution, 13th of October 2020

Economics of Nuclear Power Plants:
Review of recent trends and analysis of future trends

Source: EDF



Source: DIW

Technische Universität Berlin

DIW BERLIN

Ben Wealer (WIP/DIW), Claudia Kemfert (DIW), and Christian von Hirschhausen (WIP/DIW)

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.

Agenda

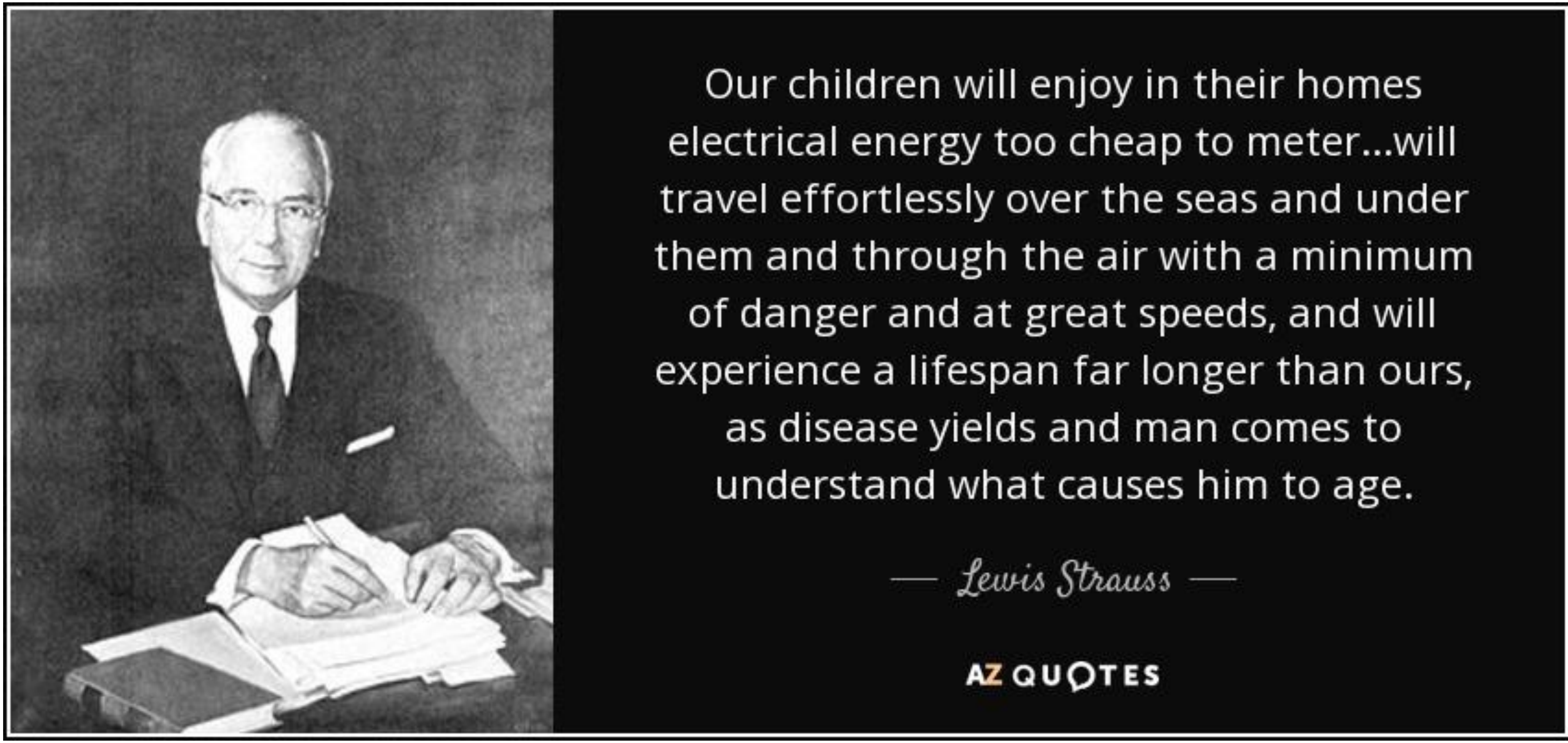
1) Some global trends
2) Demand side or „who is constructing?“
3) Supply side and technological trends
4) The perspectives of nuclear power
5) Conclusion

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**

Looking back…

The dream (1954) …

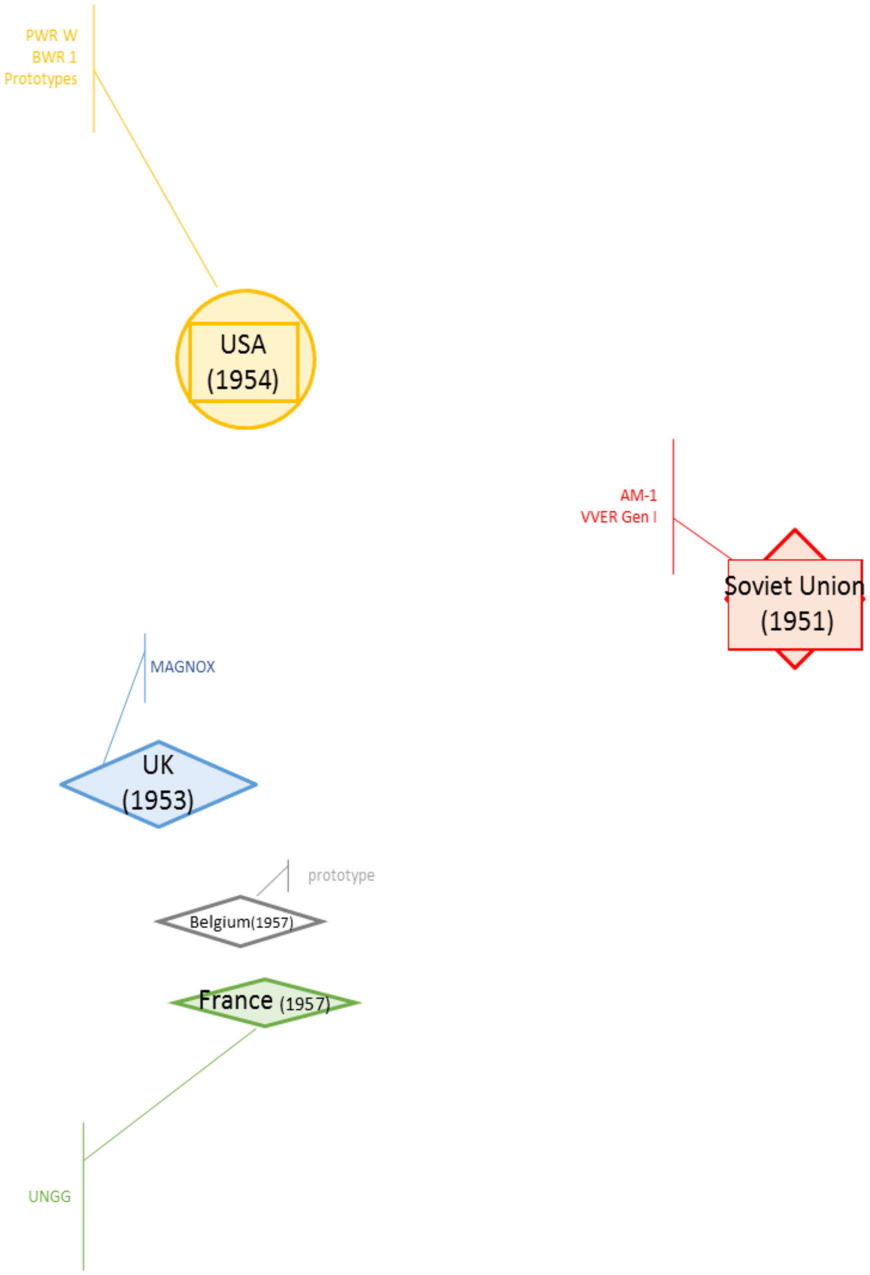


Our children will enjoy in their homes electrical energy too cheap to meter...will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speeds, and will experience a lifespan far longer than ours, as disease yields and man comes to understand what causes him to age.

— Lewis Strauss —

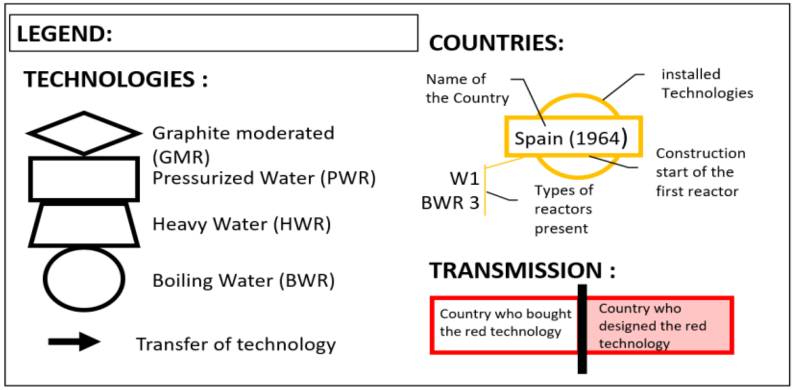
AZ QUOTES

… destroyed in … 1957: Shippingport, first „commercial demonstration reactor“: 8 times more expensive than the competitors (Radkau, 1983)

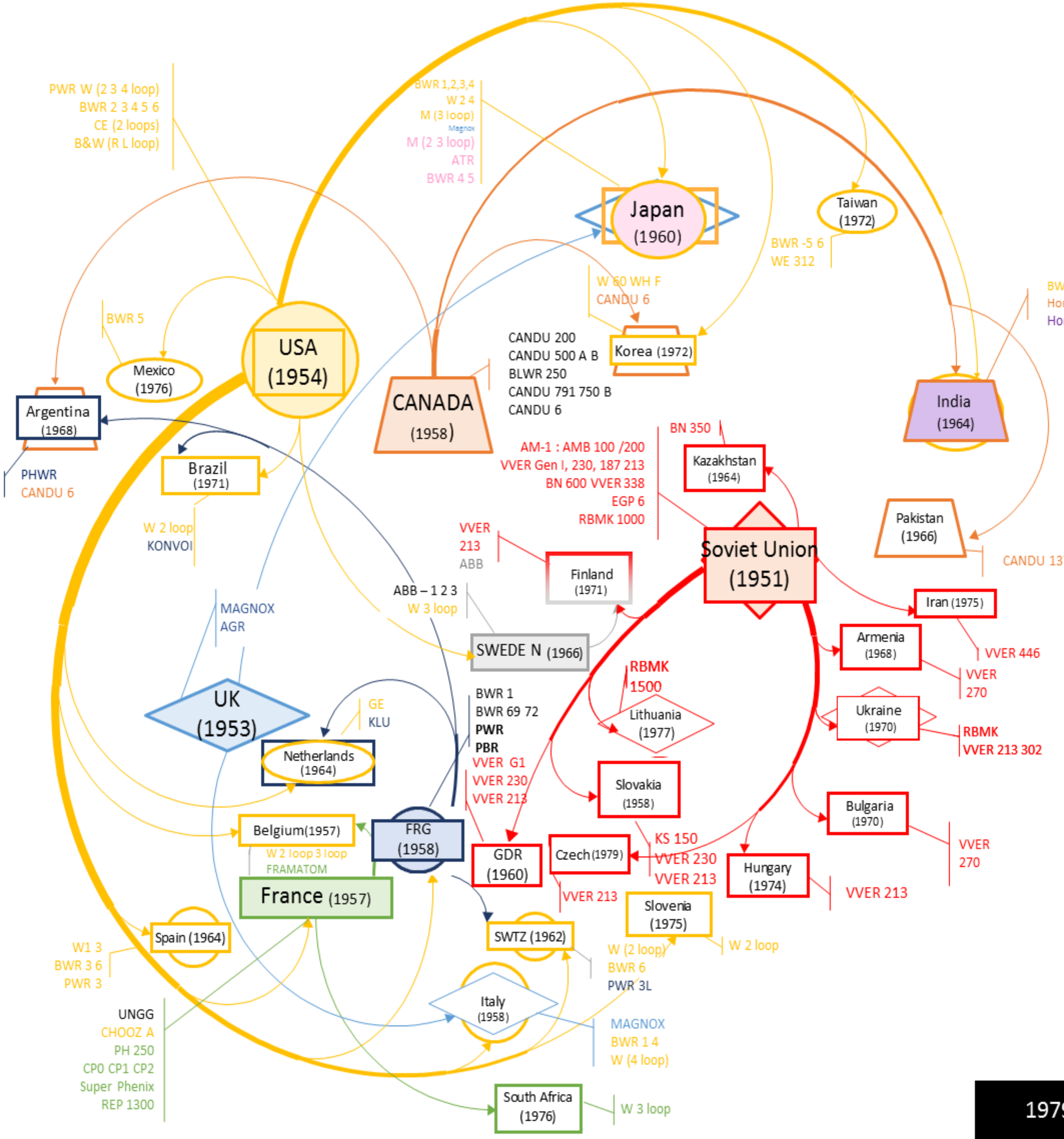


Period 1, 1945-mid 1950s:

- The origins of nuclear power: science and warfare (Lévêque 2014)
- 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.

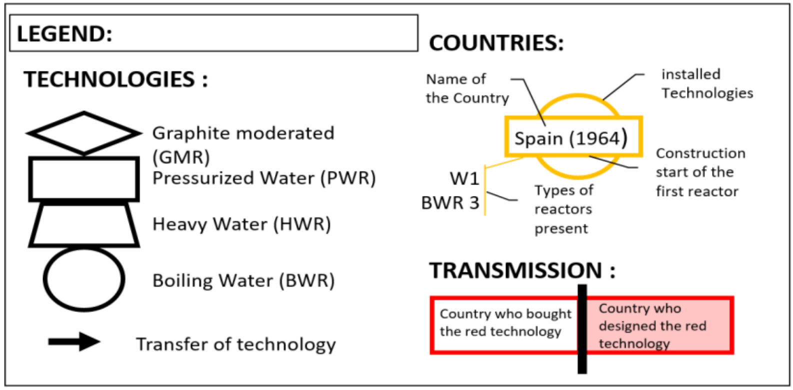


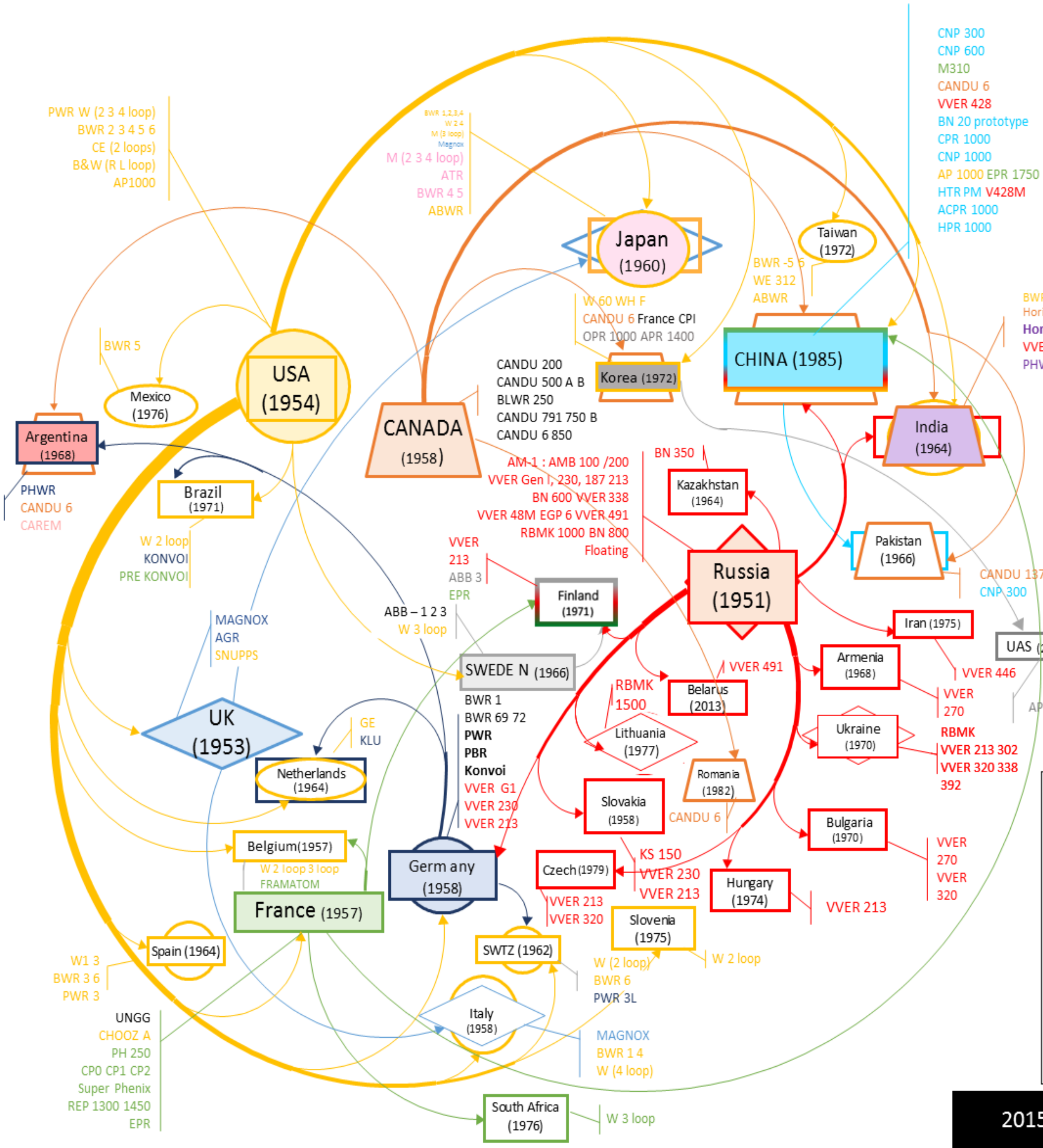
1957



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.



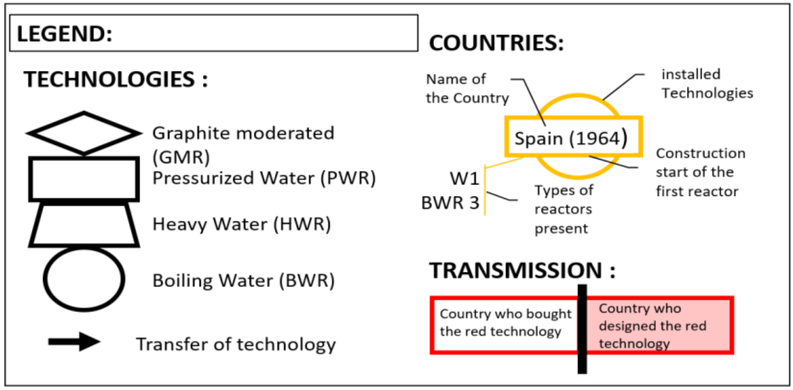


Period 3, mid-1980s- 2011:

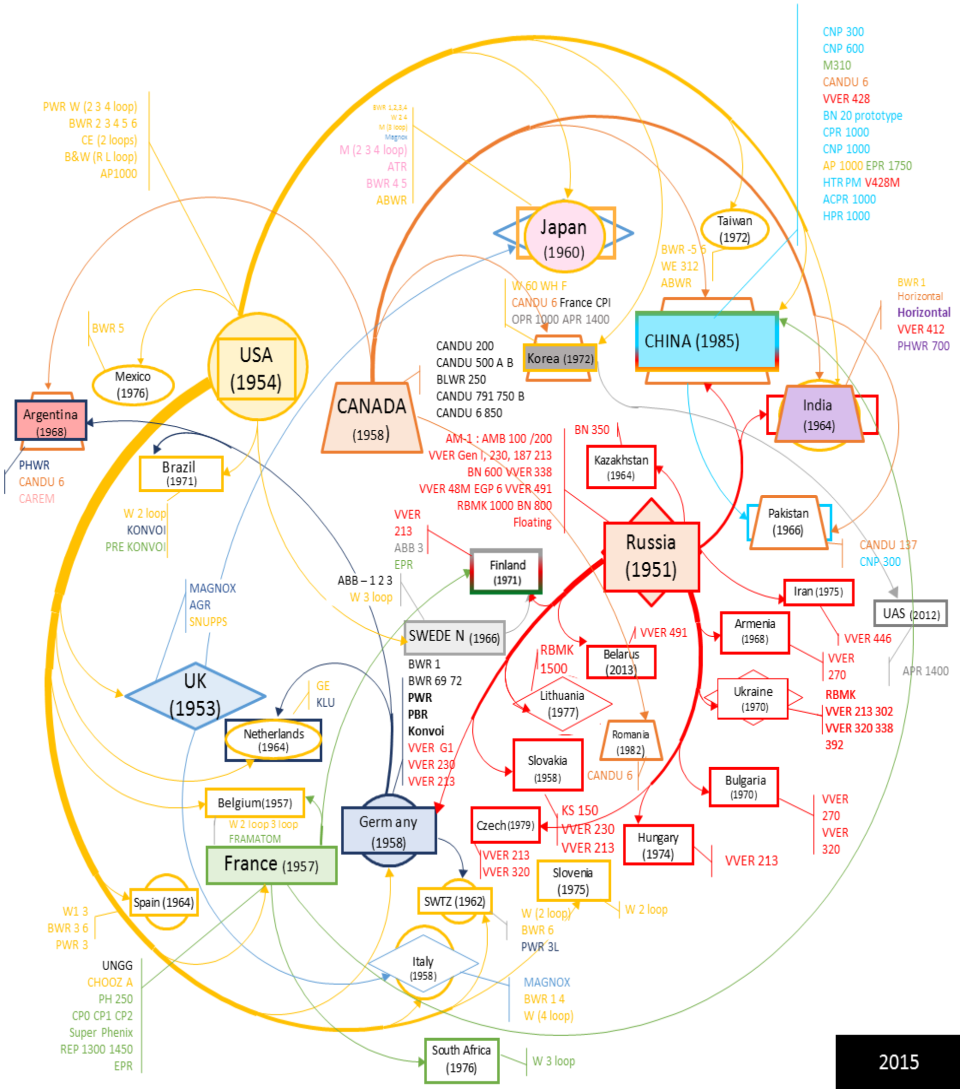
- China developed its nuclear sector, to become the third nuclear superpower.

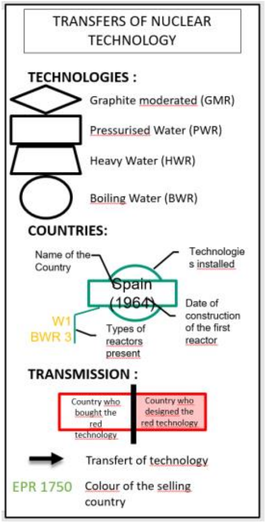
Period 4, post Fukushima:

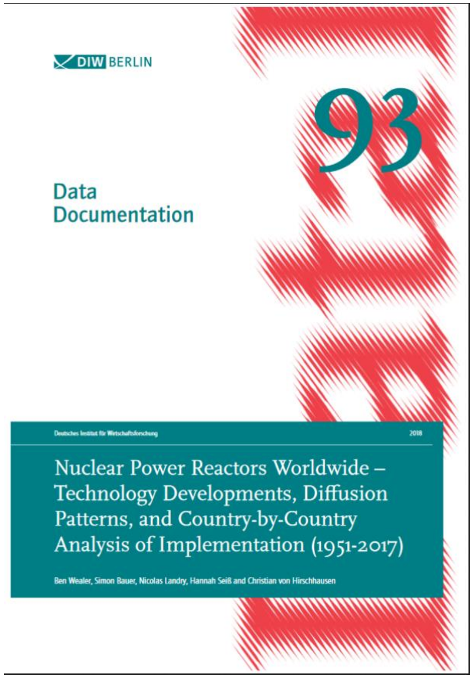
- characterized by implosion of nuclear power in Western economies (i.e. closure of reactors, abandonment of new build projects).
- This leaves the development of nuclear power to “other”, non-market systems, mainly China and Russia.



Wealer et al. (2018): Nuclear Power Reactors Worldwide







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Data Documentation

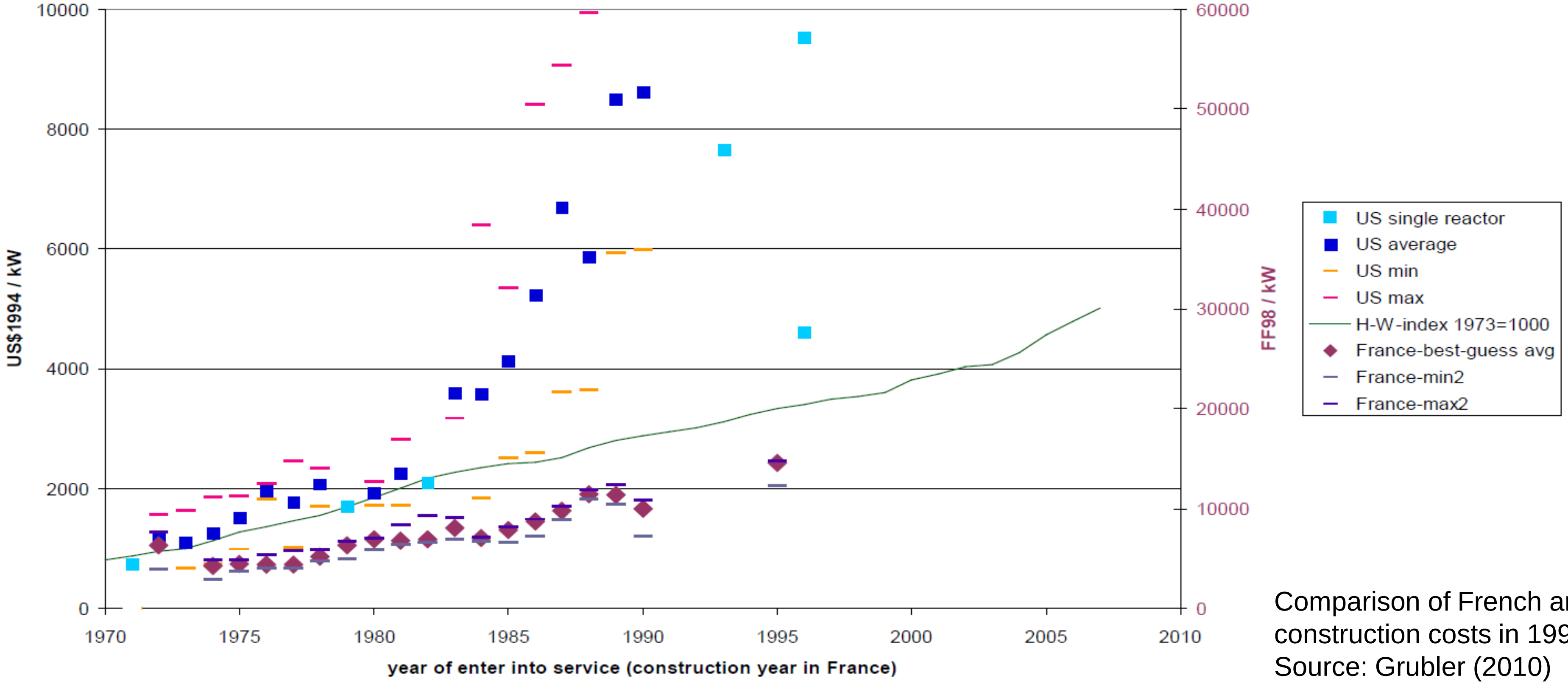
Deutsches Institut für Wirtschaftsforschung 2018

Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951-2017)

Ben Wealer, Simon Bauer, Nicolas Landry, Hannah Seiß and Christian von Hirschhausen

None of the 674 or so reactors analysed in the text and documented in the appendix, has been developed based on what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system.

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 different institutional settings. 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.”*

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

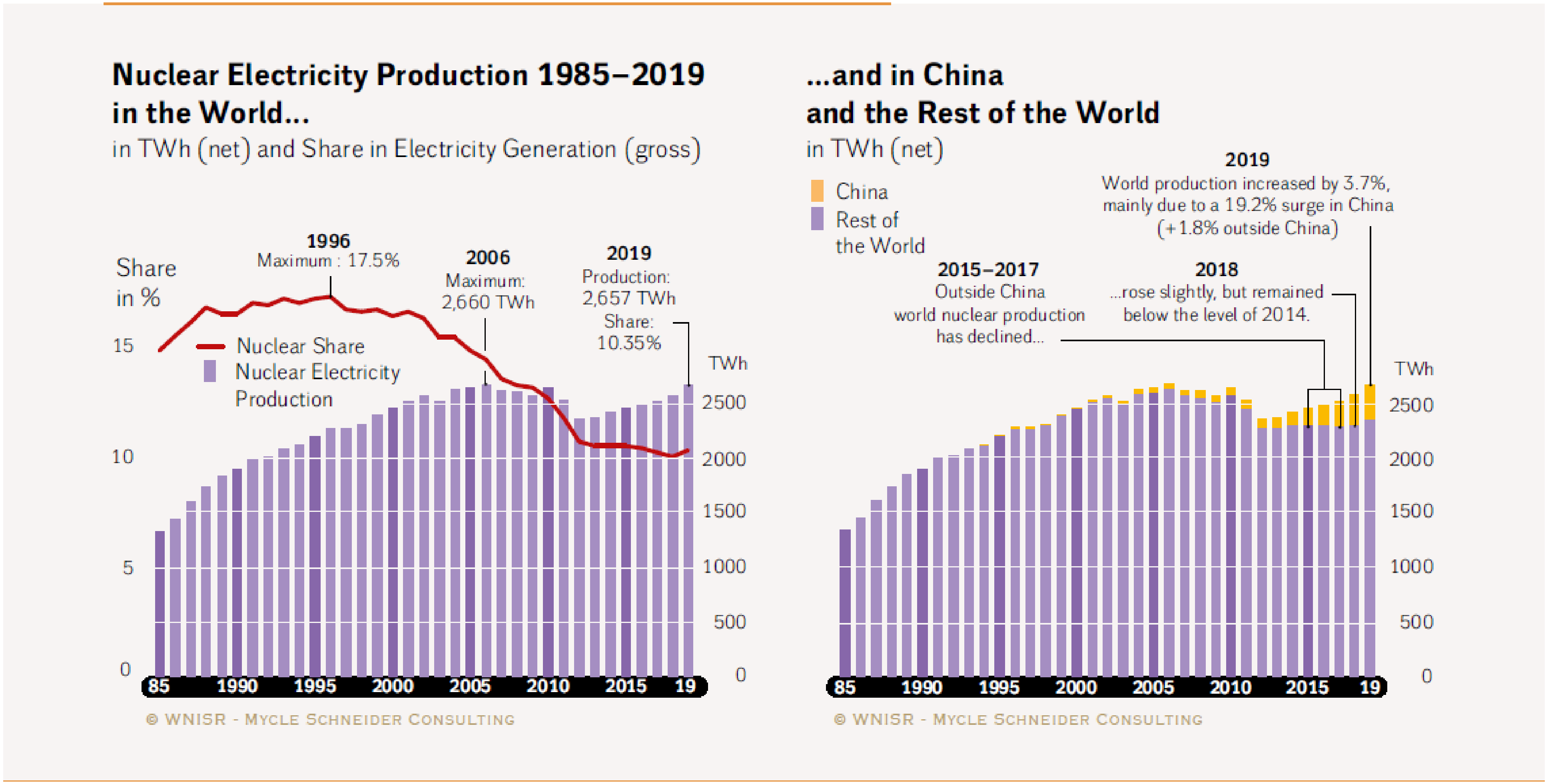
> “Nuclear new build is highly capital intensive and currently not cheap, … it is up to the nuclear sector itself to demonstrate on the ground that cost-effective construction is possible.” (p. 3)

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

> “These external costs are in addition to substantial private costs. In 1942, with a shoestring budget in an abandoned squash court at the University of Chicago, Enrico Fermi demonstrated that electricity could be generated using a self-sustaining nuclear reaction. Seventy years later the industry is still trying to demonstrate how this can be scaled up cheaply enough to compete with coal and natural gas.“ (p. 63)

Today…

Global Overview – Role of Nuclear Power



Nuclear Electricity Production 1985–2019 in the World...

in TWh (net) and Share in Electricity Generation (gross)

1996
Maximum : 17.5%

2006
Maximum:
2,660 TWh

2019
Production:
2,657 TWh
Share:
10.35%

...and in China and the Rest of the World

in TWh (net)

2019
World production increased by 3.7%, mainly due to a 19.2% surge in China (+1.8% outside China)

2015–2017
Outside China world nuclear production has declined...

2018
...rose slightly, but remained below the level of 2014.

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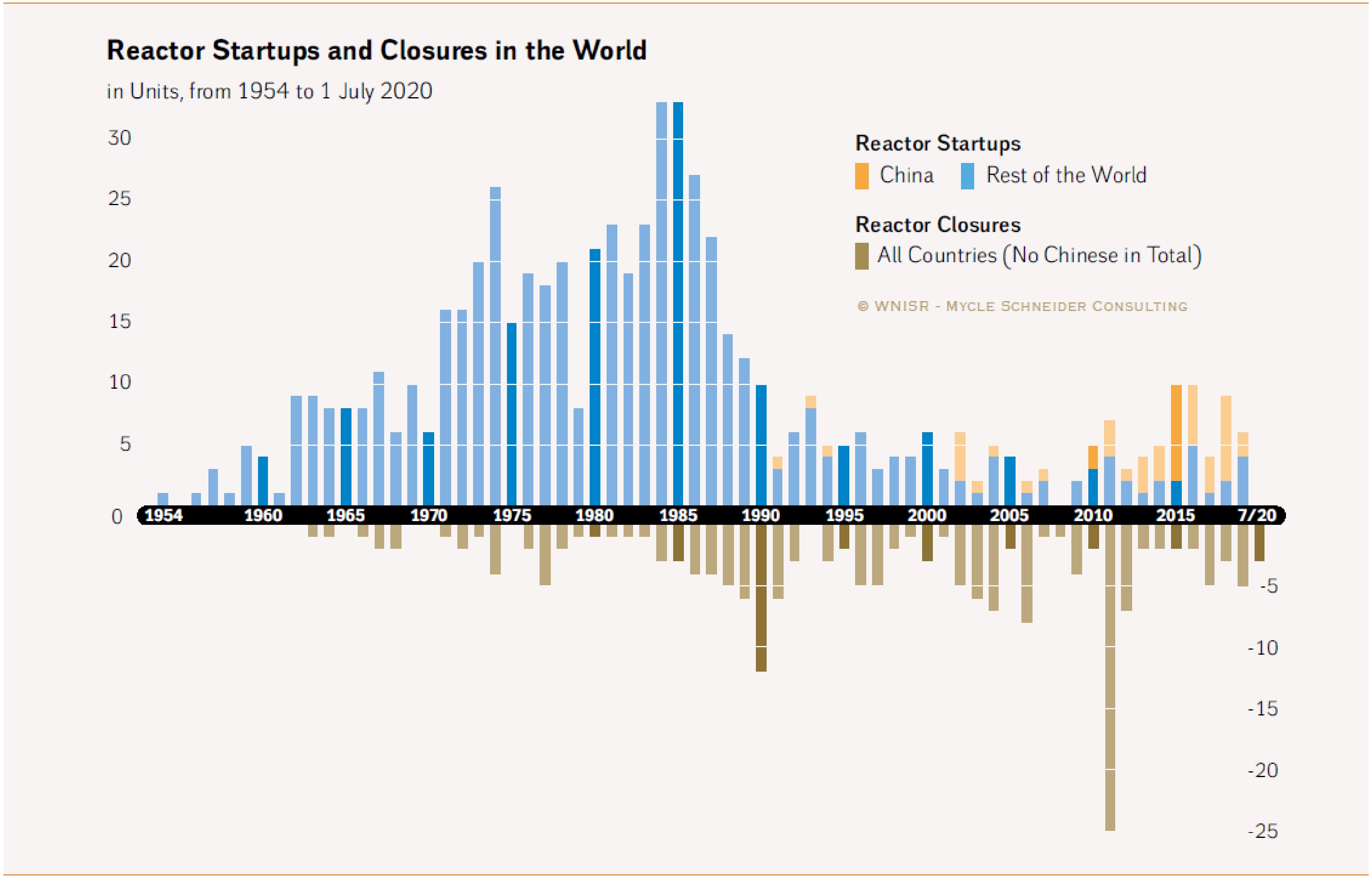
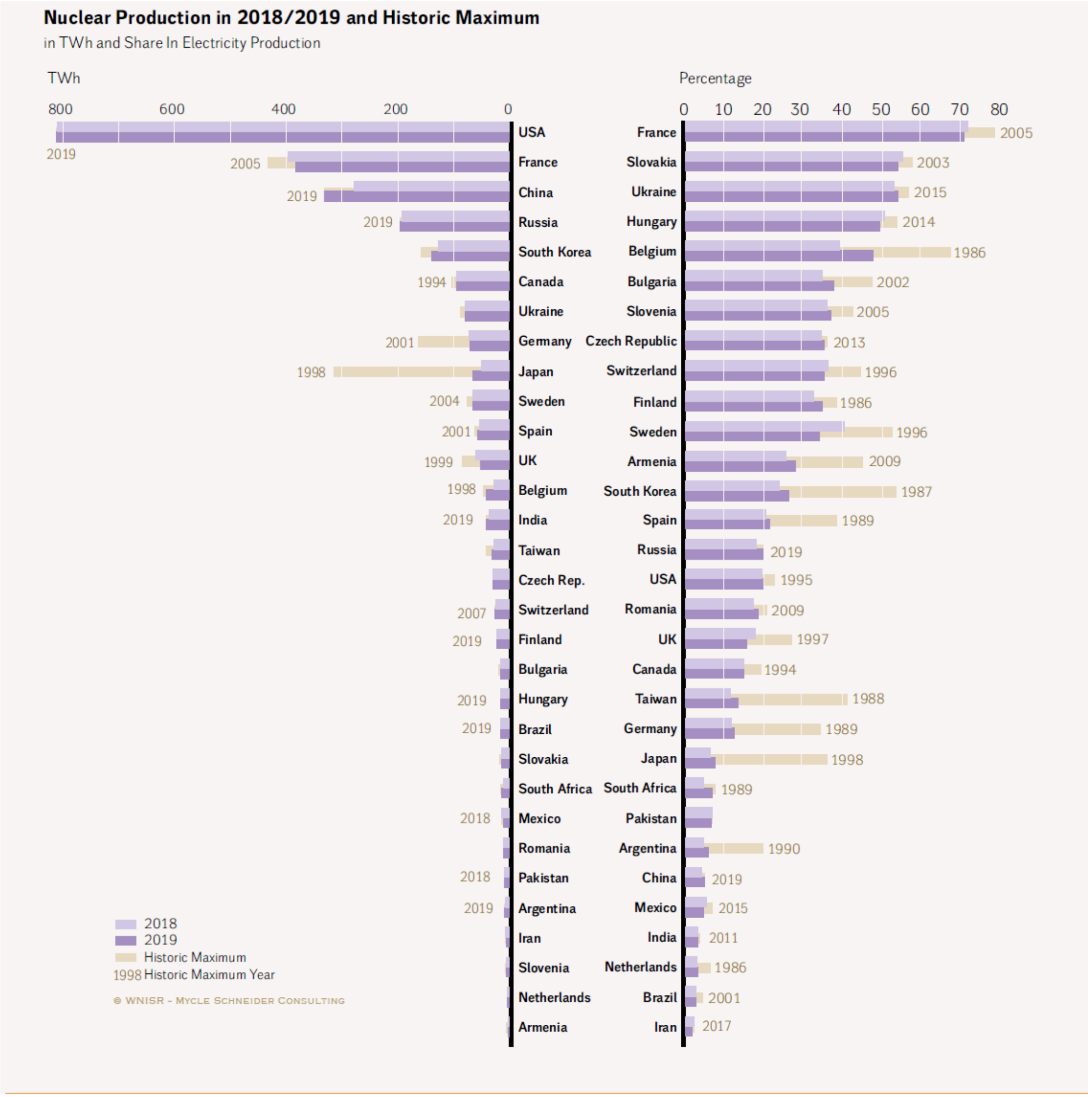
Sources: WNISR, with BP, IAEA-PRIS, 2020[42]

Global Overview – Reactor Start Ups and Closures



Sources: WNISR, with IAEA-PRIS, 2020

Global Overview – Role of Nuclear Power


Nuclear Production in 2018/2019 and Historic Maximum

in TWh and Share In Electricity Production

Sources: IAEA-PRIS, and national sources for Germany and Switzerland, 2020

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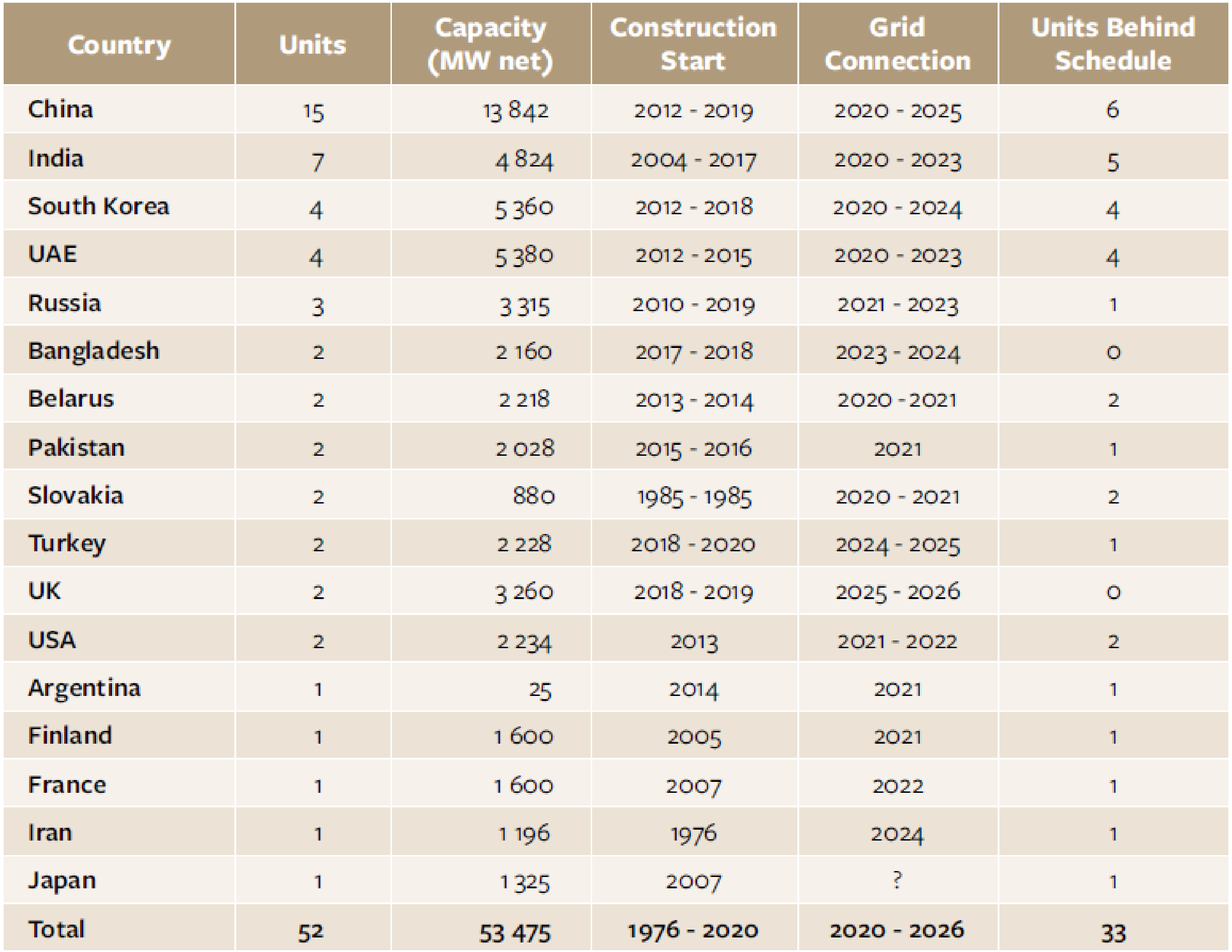
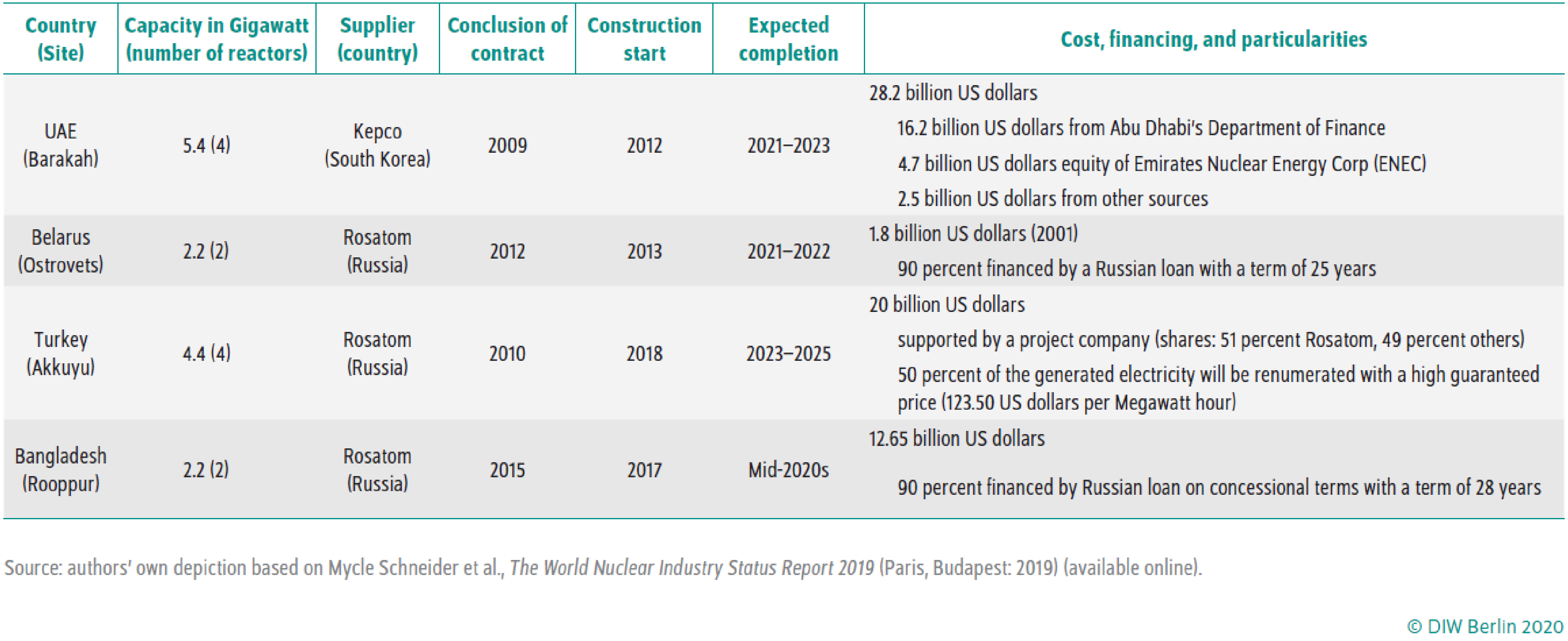
Reactors under construction



Country	Units	Capacity (MW net)	Construction Start	Grid Connection	Units Behind Schedule
China	15	13 842	2012 - 2019	2020 - 2025	6
India	7	4 824	2004 - 2017	2020 - 2023	5
South Korea	4	5 360	2012 - 2018	2020 - 2024	4
UAE	4	5 380	2012 - 2015	2020 - 2023	4
Russia	3	3 315	2010 - 2019	2021 - 2023	1
Bangladesh	2	2 160	2017 - 2018	2023 - 2024	0
Belarus	2	2 218	2013 - 2014	2020 - 2021	2
Pakistan	2	2 028	2015 - 2016	2021	1
Slovakia	2	880	1985 - 1985	2020 - 2021	2
Turkey	2	2 228	2018 - 2020	2024 - 2025	1
UK	2	3 260	2018 - 2019	2025 - 2026	0
USA	2	2 234	2013	2021 - 2022	2
Argentina	1	25	2014	2021	1
Finland	1	1 600	2005	2021	1
France	1	1 600	2007	2022	1
Iran	1	1 196	1976	2024	1
Japan	1	1 325	2007	?	1
Total	**52**	**53 475**	**1976 - 2020**	**2020 - 2026**	**33**

Sources: Various, Compiled by WNISR, 2020

Overview over the current construction projects in four newcomer countries



Country (Site)	Capacity in Gigawatt (number of reactors)	Supplier (country)	Conclusion of contract	Construction start	Expected completion	Cost, financing, and particularities
UAE (Barakah)	5.4 (4)	Kepco (South Korea)	2009	2012	2021–2023	28.2 billion US dollars 16.2 billion US dollars from Abu Dhabi's Department of Finance 4.7 billion US dollars equity of Emirates Nuclear Energy Corp (ENEC) 2.5 billion US dollars from other sources
Belarus (Ostrovets)	2.2 (2)	Rosatom (Russia)	2012	2013	2021–2022	1.8 billion US dollars (2001) 90 percent financed by a Russian loan with a term of 25 years
Turkey (Akkuyu)	4.4 (4)	Rosatom (Russia)	2010	2018	2023–2025	20 billion US dollars supported by a project company (shares: 51 percent Rosatom, 49 percent others) 50 percent of the generated electricity will be renumerated with a high guaranteed price (123.50 US dollars per Megawatt hour)
Bangladesh (Rooppur)	2.2 (2)	Rosatom (Russia)	2015	2017	Mid-2020s	12.65 billion US dollars 90 percent financed by Russian loan on concessional terms with a term of 28 years

Source: authors' own depiction based on Mycle Schneider et al., *The World Nuclear Industry Status Report 2019* (Paris, Budapest: 2019) (available online).

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Future investments consist of third generation reactors

Gen I reactors are all shut down today.

Gen II reactors constitute the major part of today's installed nuclear capacity and are still being built today (e.g., in China, India, and Slovakia).

Gen III reactors are Light Water Reactors (LWRs) and are supposed to have:

- an improved thermal efficiency,
- a more standardized and modular design,
- improved and more passive safety systems,
- and a potential longer operating life of up to 60 years.

Gen III+ designs are considered as:

- evolutionary designs and as transitional technologies until Gen IV reactors would become available
- some designs include core catchers and
- after the 9/11 attack requirements to withstand aircraft impact were added.
- Gen III+ reactors are said to rely even more on natural processes and passive systems.

Operational third generation (Gen III/III+) reactors

- **First Gen III reactor connected to the grid in 1996 in Japan.**
- **Only 24 NPPs or 26 GW connected to the grid (~ 7% of current operational capacity).**
- **Supply side: majority supplied by Rosatom.**
- **In early 2020: Only China and Russia operate Gen III+ reactors.**
- **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.**

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**

Overview of completed Gen III/III+ construction projects and average construction duration by country, as of 13th of March 2020

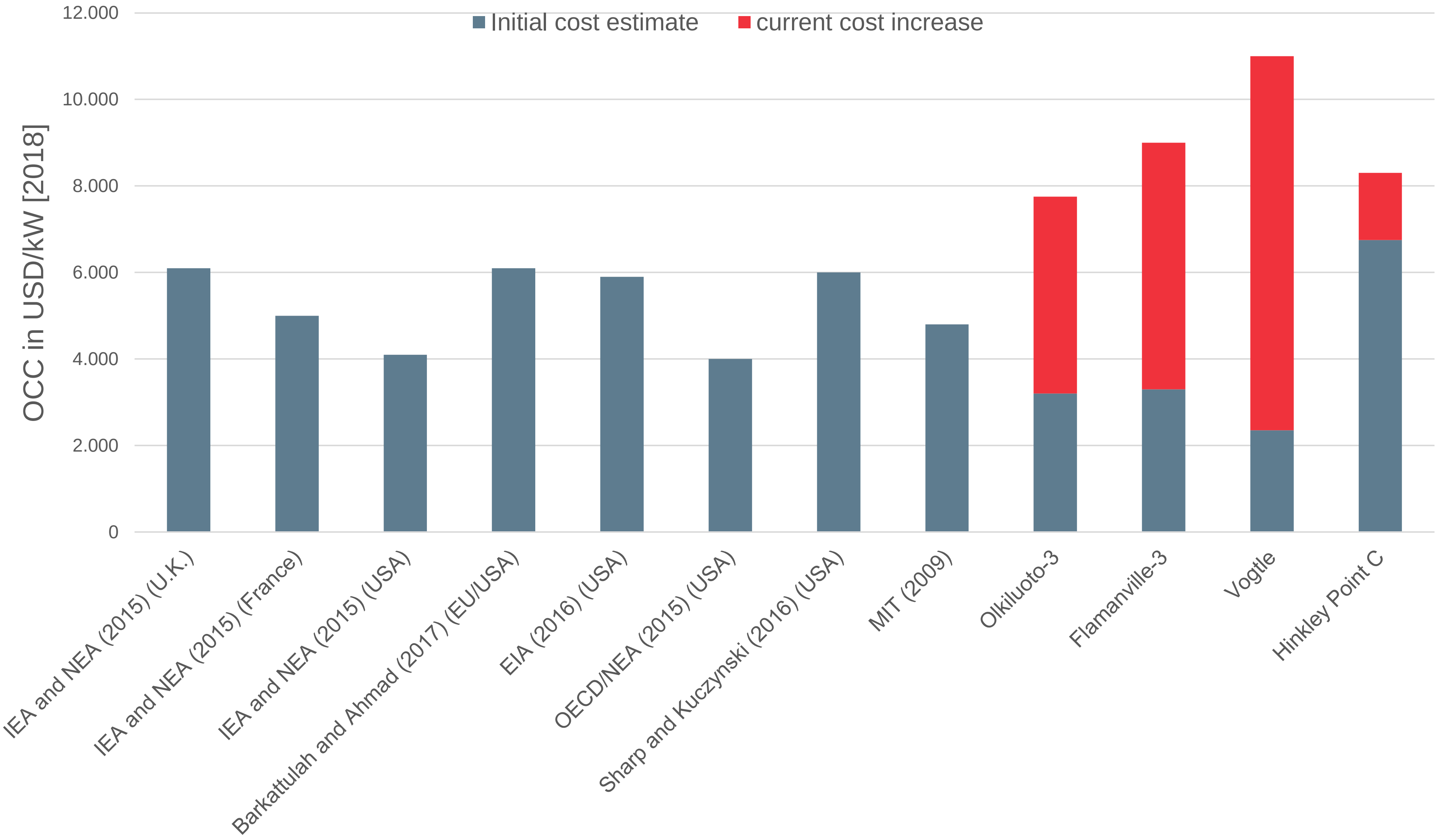
Not One Gen III/III+ Reactor Was Completed in the Western Economies

- 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.

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



Source: Own depiction

The top three reactor vendor countries are Russia, China, and Korea

- **The majority of the current new-build projects is situated in Asia and in the former USSR and is 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

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The economic perspectives…

Investing into third generation nuclear powers plants

Research Question / Objectives:

- What can a private investor expect when he 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.

Main Findings:

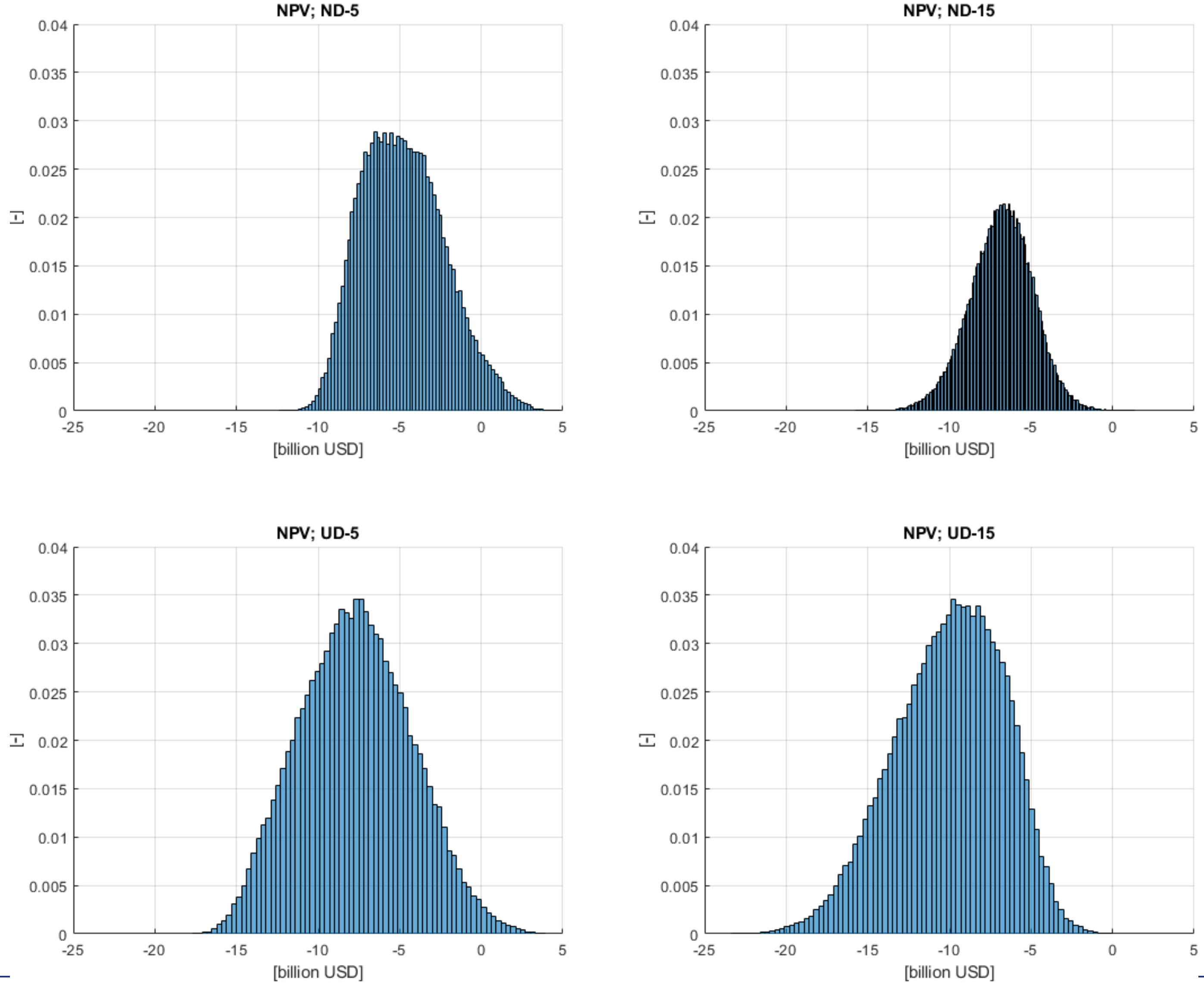
- Even without accounting for decommissioning and waste management costs the expected net present values are highly negative in most of the cases, in the range of several billion USD.
- Longer lifetimes made possible by new reactor design is no game changer for profitability.
- The results also confirm 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.

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

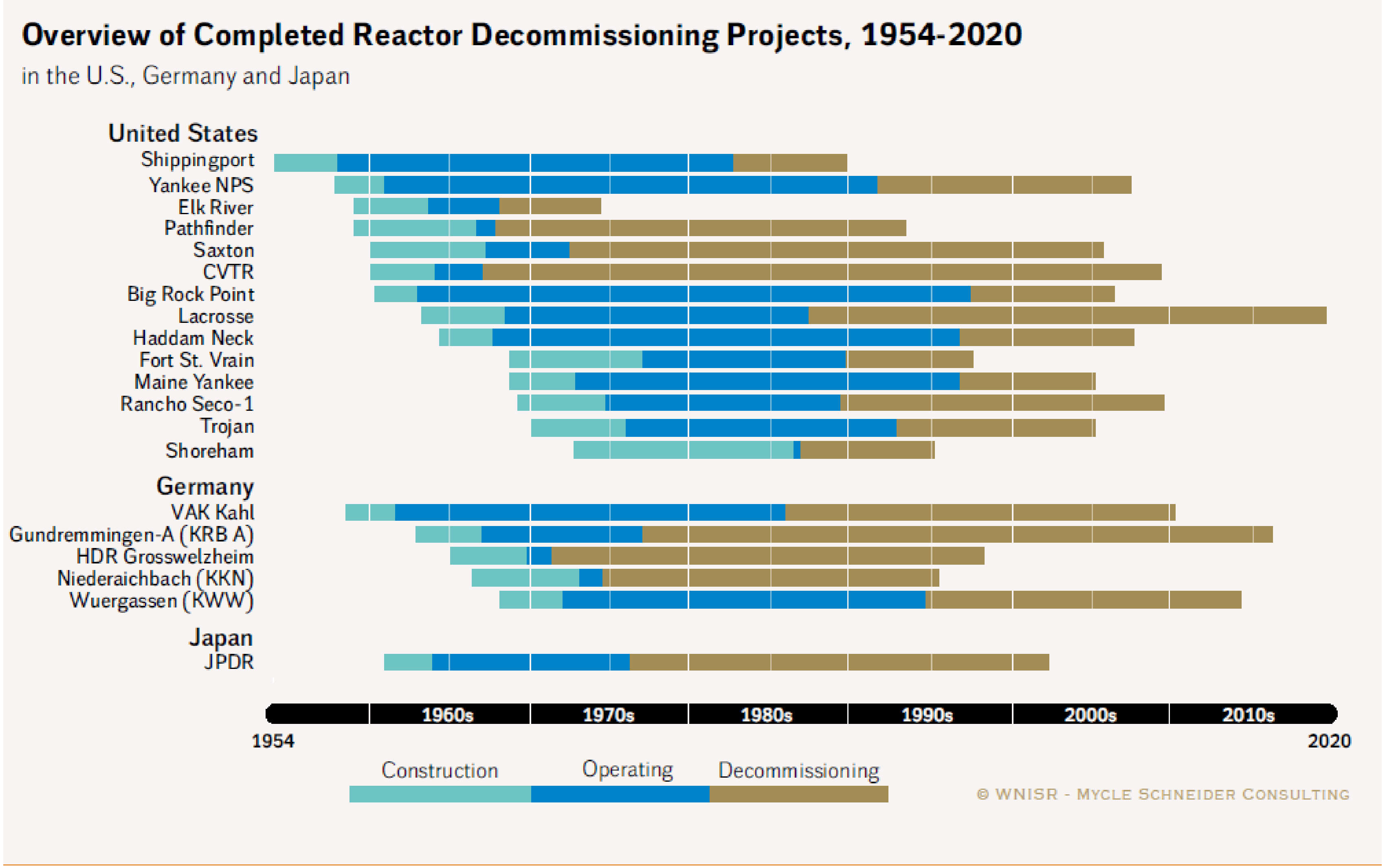
[1] Normal density suggested by Rothwell (2016).

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



The „other“ perspectives or issues …

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



Overview of Completed Reactor Decommissioning Projects, 1954-2020

in the U.S., Germany and Japan

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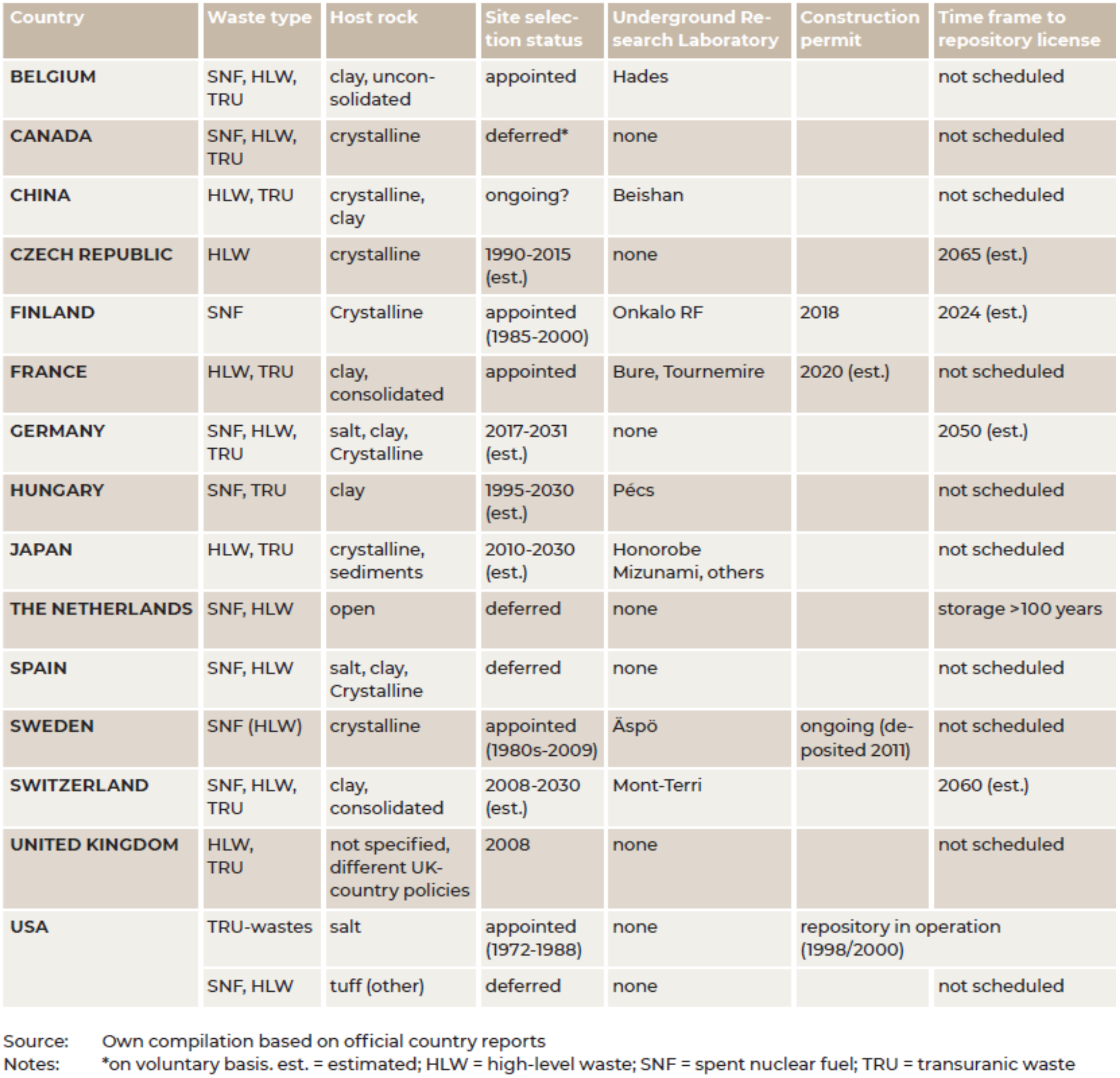
Sources: Various, compiled by WNISR, 2020

Capital Costs of Nuclear Power – Different Cost Levels

- **Only 20 reactors have been fully decommissioned**
- **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).**

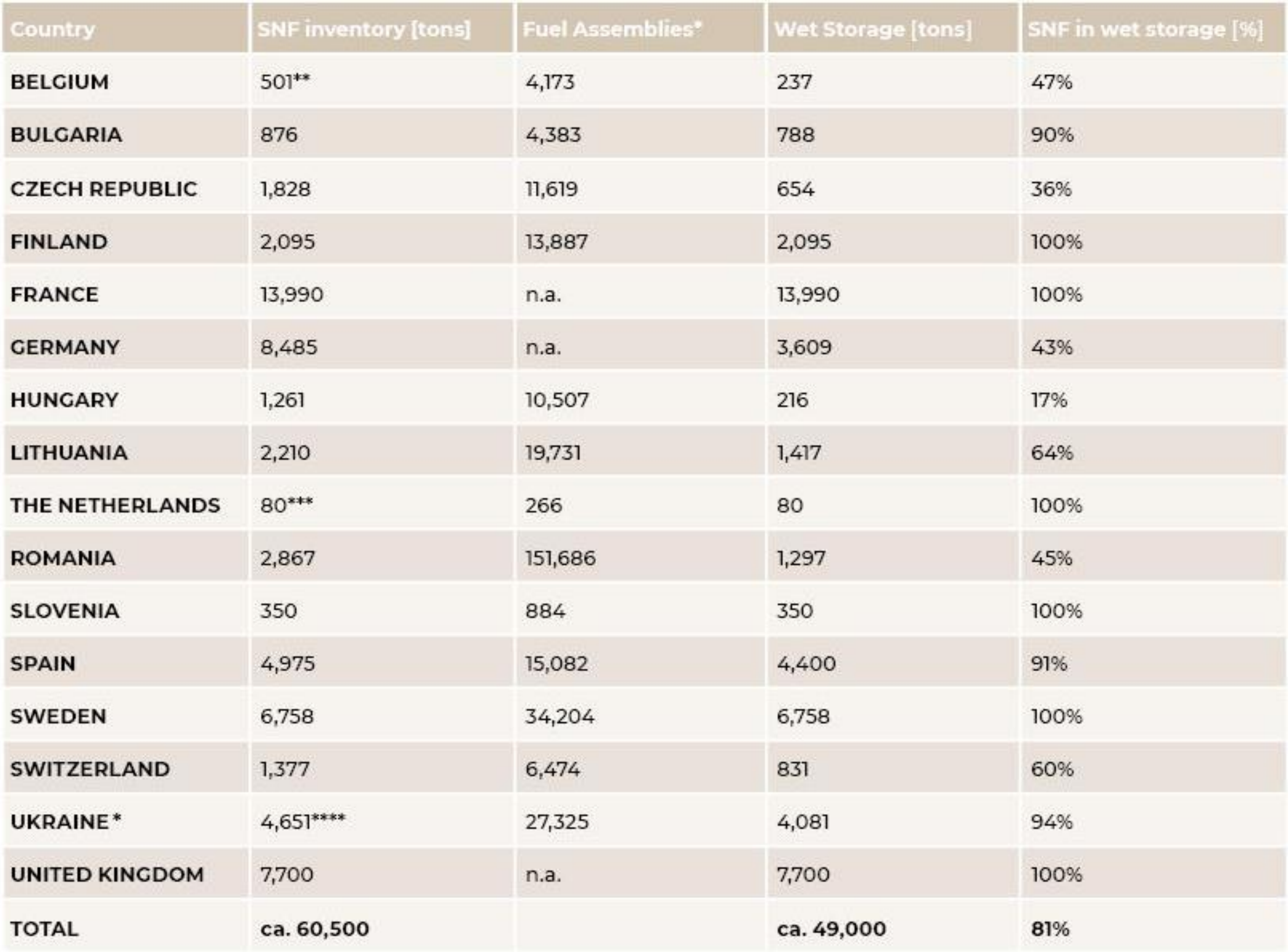
There is not one geological disposal facility in operation worldwide



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).

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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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Back-UP

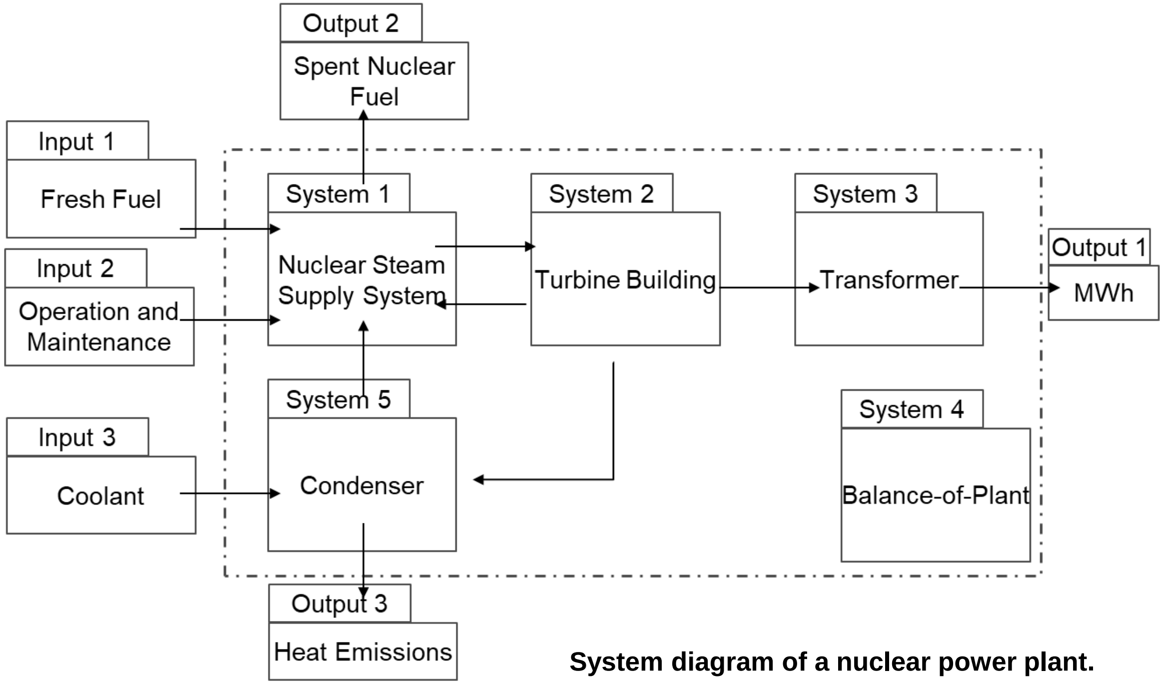
Cost breakdown for a Westinghouse AP1000

	NEA (2000)	TVA (2005)	EIA (2016)	Total DIR in %
Stuctures & improvements	460	403	863	20%
Reactor equipment	575	726	1,693	40%
Turbine generator equipment	288	484		25%
Cooling system and miscellaneous equipment	115	94		15%
Electrical equipment	173	202	314	10%
Total direct, DIR	**1,611**	**1,906**	**2,870**	
Capitalised indirect costs, INDIR	460	258		
Capitalised owner’s costs, OWN	0	322		
Supplementary costs, SUPP	0	0		
Base overnight cost, BASE	**2,071**	**2,487**		
Contingency rate	9%	16%		
Overnight cost, OC	2,261	2,875		
IDC factor, idc	14%	25%		
Total construction cost, KC	**2,577**	**3,601**	**5,945**	

Source: Own depiction based on Rothwell (2016)

„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

- **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).**

The reactor market 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).

Gen III/III+ reactor vendors and the nuclear supply chain I/II

- The low construction orders have put the traditional reactor vendors in serious financial troubles:
    - Westinghouse filed Chapter 11 bankruptcy protection in the US. and was acquired by Brookfield Business Partners for 4.6 billion USD from Toshiba Corporation in January 2018.
    - Going forward Toshiba is considering the withdrawal of all nuclear projects (Schneider et al., 2017, pp. 144–145).
    - Hitachi has never exported a reactor and its recent technology the ABWR has been proven as unreliable (Thomas, 2017b).
    - Areva: In 2017, Areva has been forced to split up and the reactor division Areva NP was sold to EDF for 2.5 billion EUR and was renamed Framatome, the company got injected with a 5 billion EUR capital increase—4.5 billion EUR stemming from the French state (Schneider et al., 2017, pp. 136–137).

Gen III/III+ reactor vendors and the nuclear supply chain II/II

- Today, the production of large components will generally be subcontracted to specialist companies and built on a one-off basis, presumably at higher cots in countries such as Japan and China.

- The supply chain for Gen III/III+ the reactor pressure vessel is the most constrained. The two major (of 5) very heavy forging capacities in operation today are:

    - Japan Steel Works (JSW) (80% of the world market share): EPR for Finland was entirely manufactured by JSW. In 2009, Westinghouse was already constrained as reactor and steam generator parts could only be delivered by JSW (World Nuclear Association, 2017).

    - Le Creusot in France, part of the Areva Group since 2006, has been in hot water in recent times and is currently being investigated due to irregularities in quality-control documentation and manufacturing defects of forged pieces produced for the EPR as well as the operational reactors, leading to multiple shutdowns in 2016.

Main results from the monte-carlo analysis

	ND-5	ND-15	UD-5	UD-15
Mean NPV [USD]	-4.77 billion	-6.82 billion	-7.71 billion	-9.97 billion
Median NPV [USD]	-4.94 billion	-6.76 billion	-7.74 billion	-9.76 billion
95 percentile NPV [USD]	-0.26 billion	-3.76 billion	-1.99 billion	-4.99 billion
Mean LCOE [USD/MWh]	91.38	168.59	116.01	221.90
Median LCOE [USD/MWh]	89.96	160.03	111.47	206.53
5 percentile LCOE [USD/MWh]	66.42	97.33	73.29	112.42

Chapter 4: 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.

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.

The Model

- Basic formula for the NPV with Rt represents the revenues, t ∈ [0,T] years, with T=T_con+T_op, r the yearly cost of capital rate. It is assumed that the cost of capital during construction equals the weighted average costs of capital (WACC).

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t}$$

$$WACC = \frac{d}{d+e} \cdot r_d + \frac{e}{d+e} r_e$$

- Following Rothwell (2016), TCC and the IDC-factor are calculated according to the following equation. The construction time T_con influences IDC exponentially.

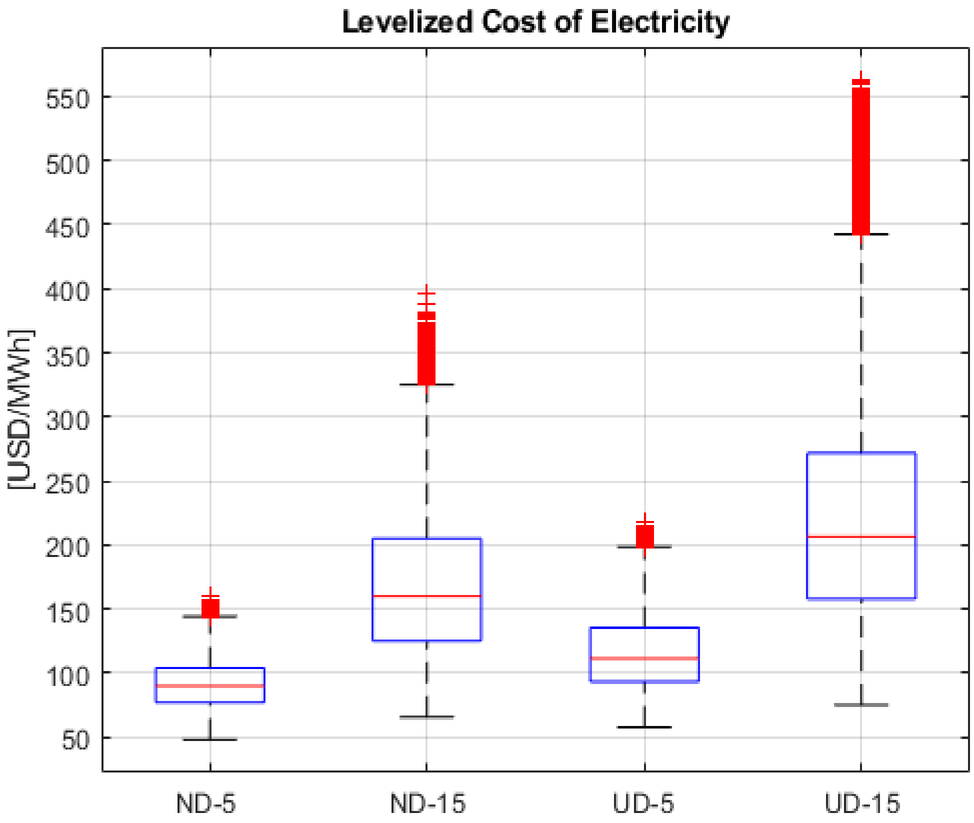
$$TCC = OCC(1 + idc)$$

$$idc \cong \frac{r}{2} \cdot T_{con} + \frac{r^2}{6} \cdot T_{con}^2$$

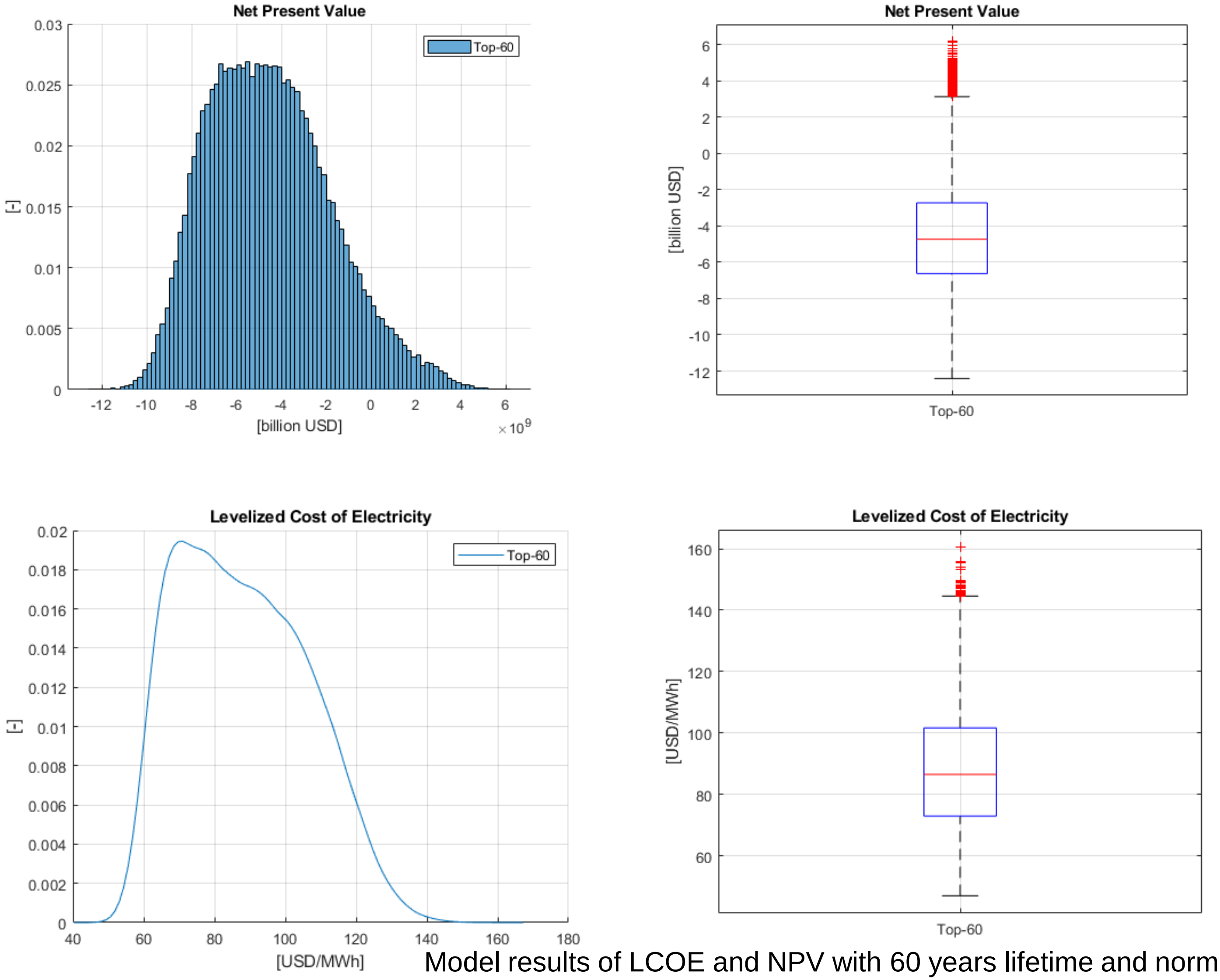
- In this paper, income is solely generated by electricity sales; expenditures comprise fixed and variable operation and maintenance (O&M) costs, fuel costs, and total construction costs (TCC).

$$LCOE = \frac{\sum_{t=0}^{T} (TCC_t + O\&M_t + Fuel_t + Carbon_t) \cdot (1+r)^{-t}}{\sum_{t=0}^{T} Electricity_t \cdot (1+r)^{-t}}$$

LCOE


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

A 60 years' lifetime improves the NPV and LCOE only marginally. The distribution of NPV highlights negative values.

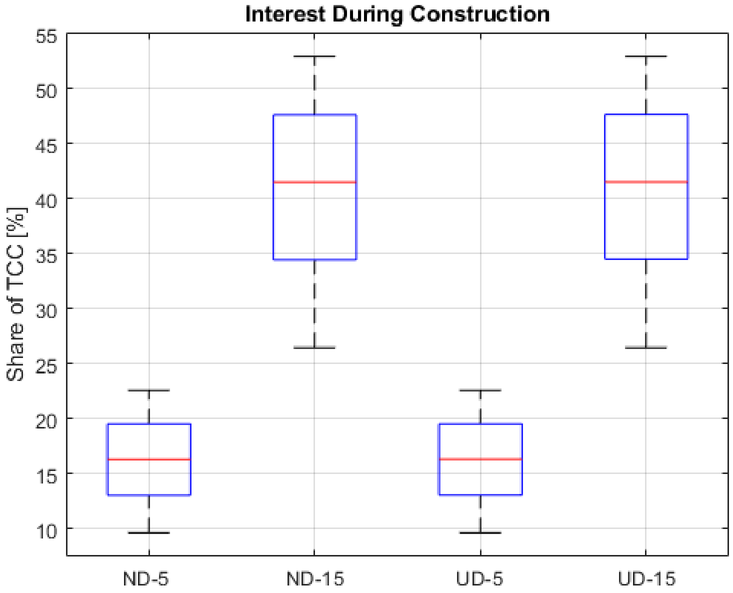


Model results of LCOE and NPV with 60 years lifetime and normal distribution of OCC

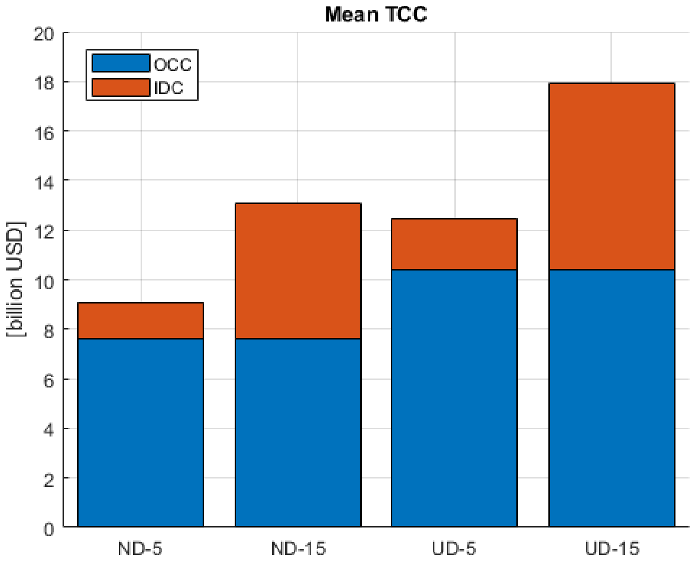
The Importance of Capital Costs

Construction costs are the major component of the LCOE and between 60-80%, depending on the cost of capital and the construction duration (MacKerron 1992; Haas, Thomas, and Ajanovic 2019).

It does not make much economic sense to compare reactor costs without including the cost of capital (Koomey, Hultman, and Grubler 2017; Haas, Thomas, and Ajanovic 2019) as nuclear power construction projects are characterized by long construction times, a period where no income is generated.



Box-whisker-plot of interest during construction (IDC) as share of TTC for all scenarios.



Mean TCC, OCC and IDC for all scenarios.