PSL energy economics seminar
12th December 2018

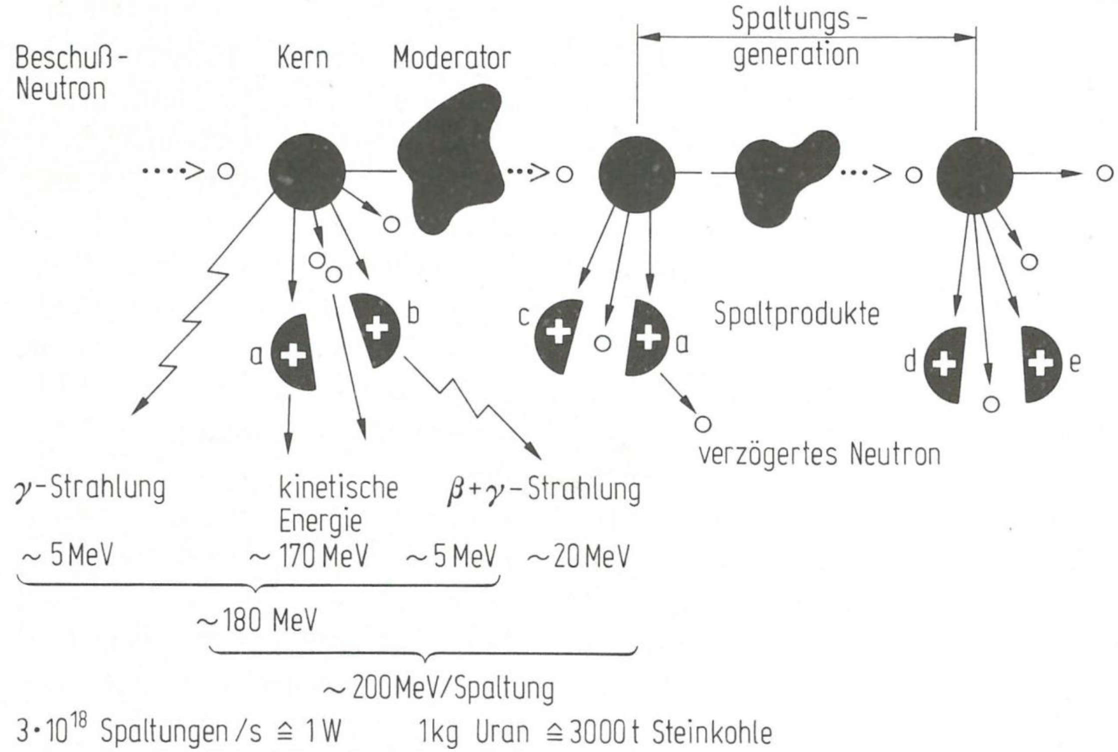
Decommissioning of Nuclear Power Plants: International Comparison of Organisational Models and Policy Perspectives

Ben Wealer (WIP/DIW)

Agenda

1) Introduction
2) Nuclear Power Economics
3) Decommissioning of Nuclear Power
    1) Global Survey
    2) France
    3) United States of America
    4) Germany
    5) Japan
4) Conclusion and Outlook

Francois Lévêque (2013):
„L‘énergie atomique est la fille de la science et de la guerre“



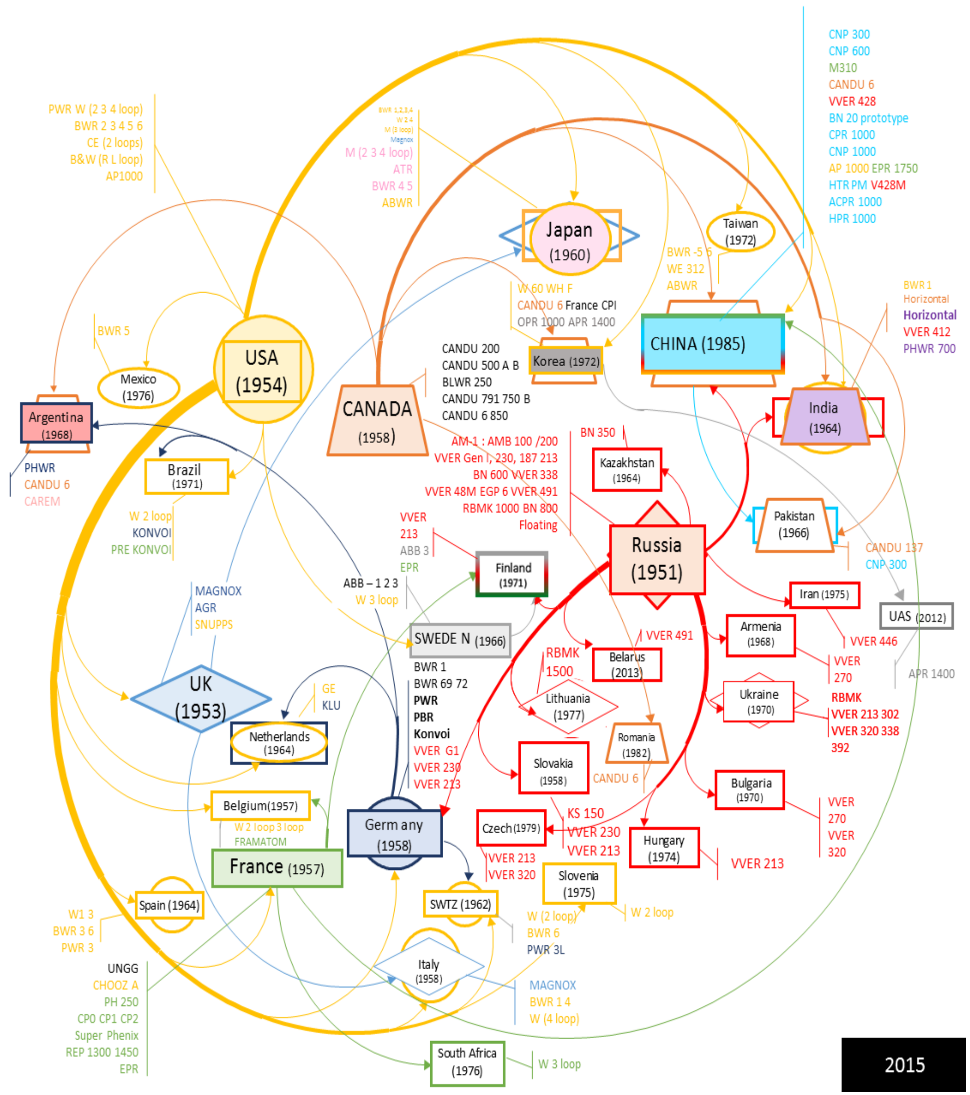
Durchschnittliche *Energieverteilung* für die Spaltung des U^{235}-Kerns in MeV:

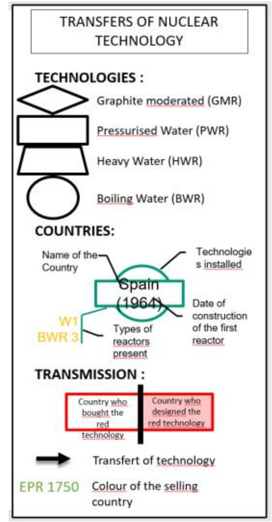
$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{89}_{36}Kr + {}^{144}_{56}Ba + 3\,{}^{1}_{0}n$$

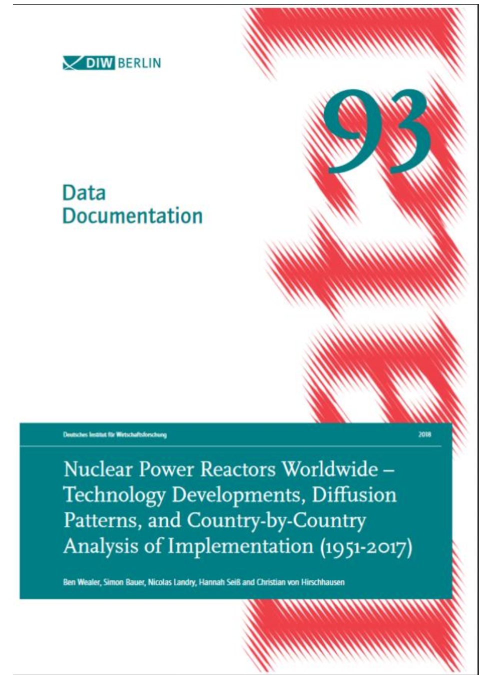
Aus-gangs-kern (Spalt-stoff)	thermi-sches Neutron 2000 m/s	kurz-lebiges Zwischen-produkt	hier Krypton	hier Barium	3 Neutronen

(als Beispiel häufiger Spaltprodukte)

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







<u>None</u> of the 674 or so reactors analysed in the text and documented in the appendix, has been <u>developed based on what is generally considered “economic” grounds</u>, i.e. the decision of private investors in the context of a market-based, competitive economic system. Given current technical and economic trends in the global energy industry, there is no reason to believe that <u>this rule will be broken in the near- or longer-term future</u>.

Agenda

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

MIT (2003, p. 3): The Future of Nuclear Power

> **“In deregulated markets, nuclear power is not now cost competitive with coal and natural gas.”**

University of Chicago (2004, p. 5-1):

> **“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.”**

Parsons/Joskow (EEEP 2012)

> **“may be one day …”**

D’haeseleer (2013, p. 3): 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, p. 63): 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)**

The perspectives of nuclear power deployment depend in the long term on…

on the development of costs, in relation to other low-carbon options, and the economics of investments into new capacities.

while there is a consensus in the literature that nuclear power is not competitive under regular market economy, competitive conditions, <u>at least two issues</u> need to be considered going forward:

- First, the treatment of “costs” in other, non-market institutional contexts:
  - such as indigenous suppliers or “home suppliers” (Thomas, 2010),
  - or the subsidized export models of countries like China (Thomas, 2017) or Russia (Hirschhausen, 2017).
- Second, the evolution of future technologies (e.g., Gen III/III+, Gen IV, SMR).

Capital Costs of Nuclear Power – Different Cost Levels

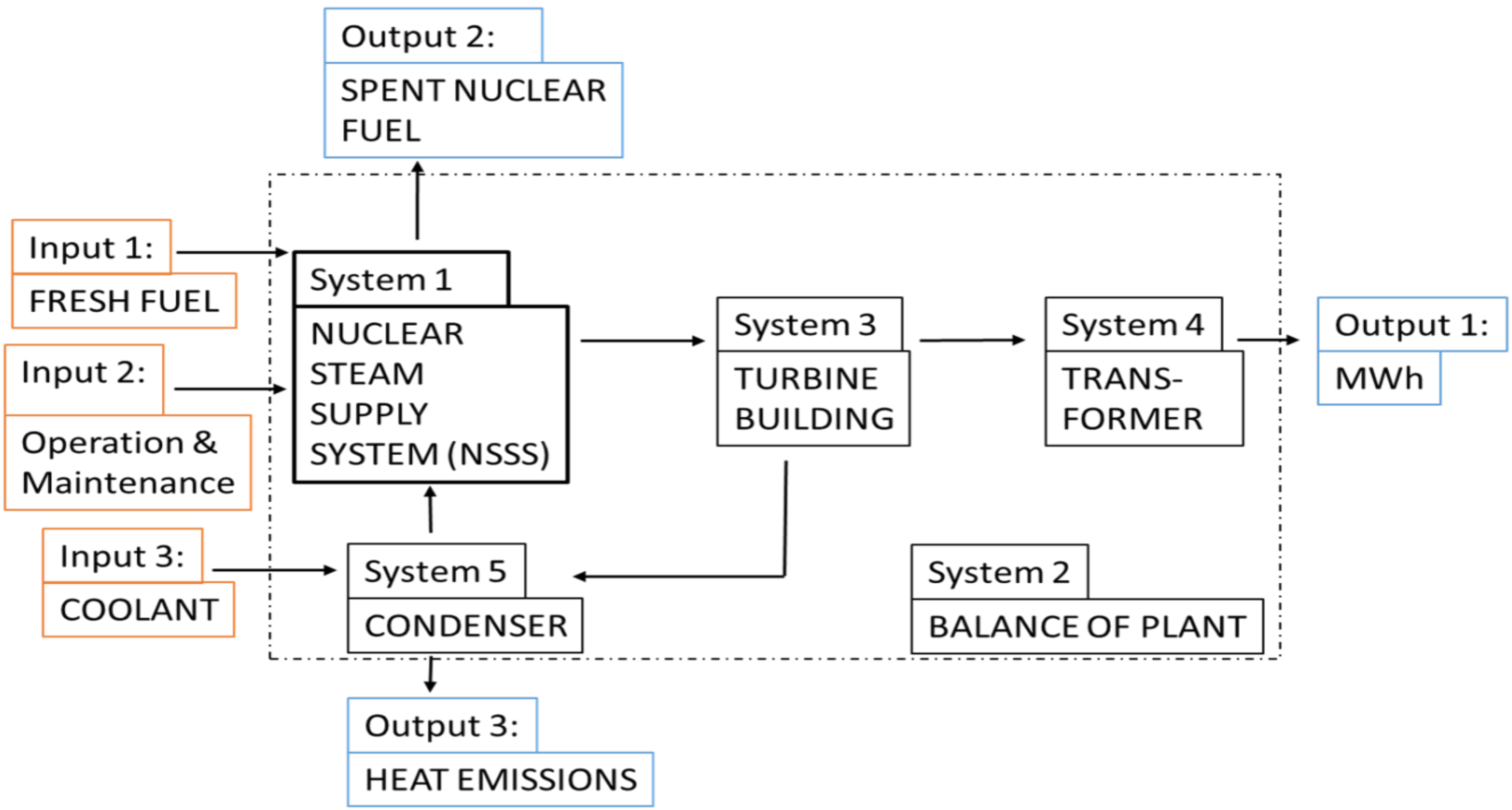
The most used indicator for comparing different generation technologies is the cost concept of "overnight construction costs" (OCC), i.e. as if the full expenditure were spent "overnight", therefore the interest during construction is not included (i.e. financing cost).

	Cost Level
	Owner's cost
+	Engineering, Procurement, and Construction costs (EPC)
+	Contingency Provision
=	**Overnight construction cost**
+	Interest during Construction (IDC)
=	**(Total) Investment Cost (TIC)**

Source: Own depiction based on D'Haeseleer (2013)

Systematic View of a nuclear power plant

One can also break down capital costs into direct costs according more or less to different systems of a nuclear power plant.
Indirect costs include construction services, engineering & home office services, and field supervision & field office services.



Source: Own depiction based on Rothwell (2016) and NRC 10 CFR §170.3

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)

Current construction projects (in 2017): 54 NPPs or 52 GW in 13 countries

Country	Construction capacity in MW (NPP)	Technologies	Generation	Supplier
Argentina	25 (1)	Carem25	SMR	Argentina
Belarus	2,218 (2)	VVER V-491	Gen III^{+} (2)	Atomstroyexport
China	19,500 (19)	ACPR-1000, HPR-1000, HTR-PM, VVER V-428M, AP-1000, EPR	Gen III (13), Gen III^{+} (6)	China, cooperation with Toshiba, Areva, and Atomstroyexport
Finland	1,600 (1)	EPR	Gen III^{+}	Framatome
France	1,600 (1)	EPR	Gen III^{+}	Framatome
India	3,907 (6)	PHWR-700, VVER-1000, Prototype FBR	Gen II (4), Gen III (1), Other (1)	Indian, Atomstroyexport
Japan	2,650 (2)	ABWR		Hitachi-GE
Pakistan	2,028 (2)	ACP-1000		China
Russia	4,359 (7)	VVER V-320, VVER V-392 M, VVER V-491, KLT-40S	Gen II (1), Gen III^{+} (4), Other (2)	Russia
Slovakia	880 (2)	VVER V-213	Gen III^{+}	Atomstroyexport
South Korea	5,360 (5)	APR-14000	Gen III	KEPCO (South Korea)
United Arab Emirates	5,380 (4)	APR-14000	Gen III	KEPCO (South Korea)
USA	2,234 (2)	AP1000	Gen III^{+}	Westinghouse
	51,741 (54)			

Source: Own depiction, for more details see Wealer et al. (2018, p. 32)

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

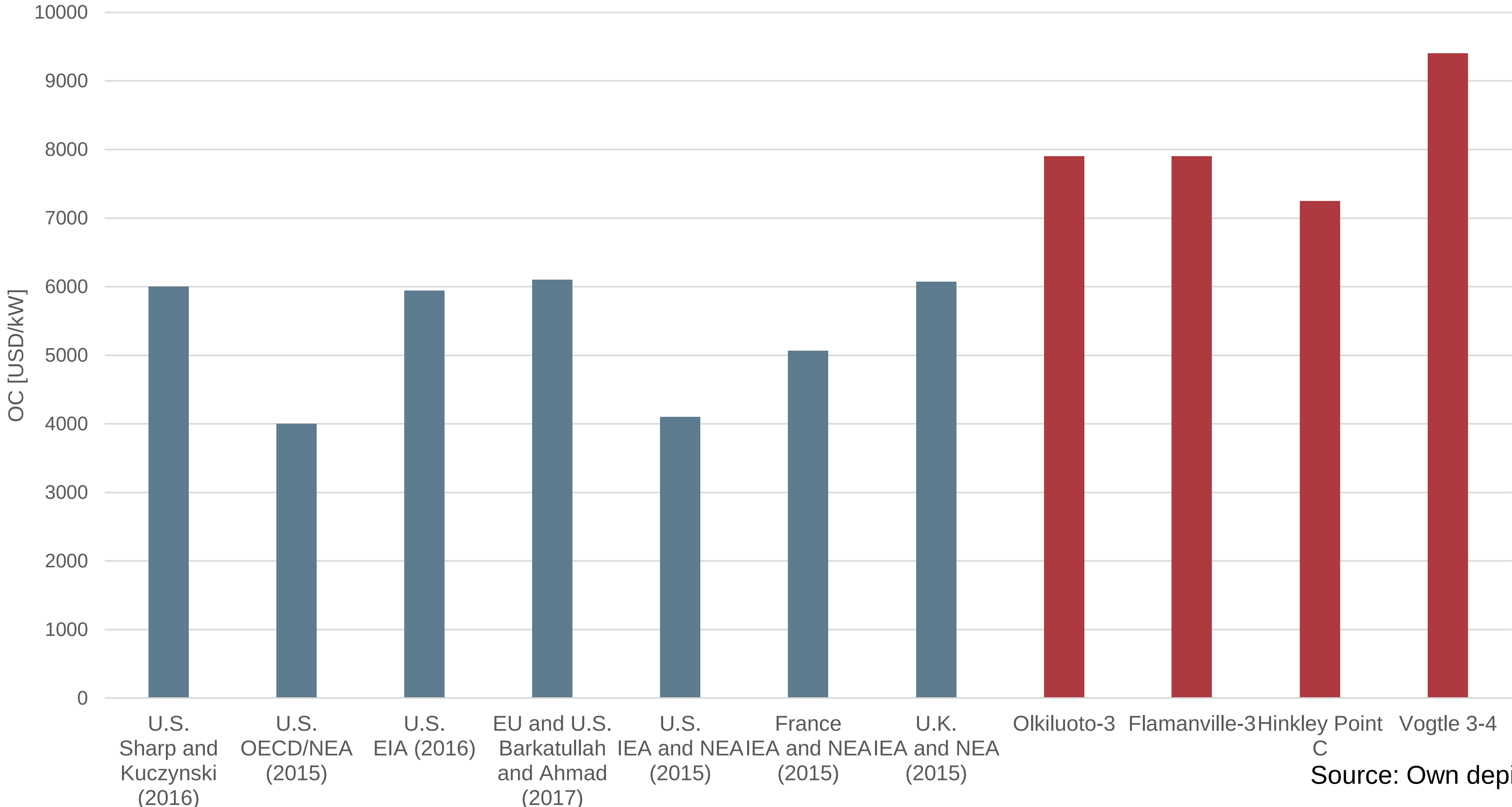
- Today, the production of large components will generally be subcontracted to specialist companies and built on a one-off basis, presumably at higher cots in countries such as Japan and China.

- 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.

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



Source: Own depiction

Cost estimations have to be regarded critically, as no Gen III/III+ reactors has been successfully connected to the grid in the US or Europe. As always all these cost figures omit costs for decommissioning and waste disposal.

Davis (2012; JEP, p. 11): „70 years later …“ current update for Europe (own calc.)

Table 3

Levelized Cost Comparison for Electricity Generation

	Levelized cost in cents per kWh		
Source	*Nuclear*	*Coal*	*Natural gas*
MIT (2009) baseline	8.7	6.5	6.7
Updated construction costs	10.4	7.0	6.9
Updated construction costs and fuel prices	10.5	7.4	5.2
With carbon tax of $25 per ton CO_2	10.5	9.6	6.2

	Levelized costs in €cents/kWh		
	Nuclear	Coal	Natural Gas
Baseline (2016)	11	5,1	5,0
CO_2-price: 25 €/t	11	6,3	5,7
CO_2-price: 100 €/t	11	10,0	7,9

Source: own calculation

Nuclear power – profitability check

General assumptions:

- **Investment**
  - Overnight cost: 6.000 €/kW
  - Installed capacity: 1.100 MW
  - Initial investment: 20 years
  - Plant lifetime: 50 years
- **Fixed and variable costs**
  - Fixed operating costs:
    - Operation 20 €/kW/year
    - Maintenance 20 €/kW/year
    - Insurance 15 €/kW/year
  - Variable operating costs:
    - Operation 8 €/MWhel
    - Maintenance 7 €/MWhel
  - Fuel price: 1,5 €/MWhth
  - Electric efficiency: 38%
  - Full load Hours: 6.500 h

Calculation results:

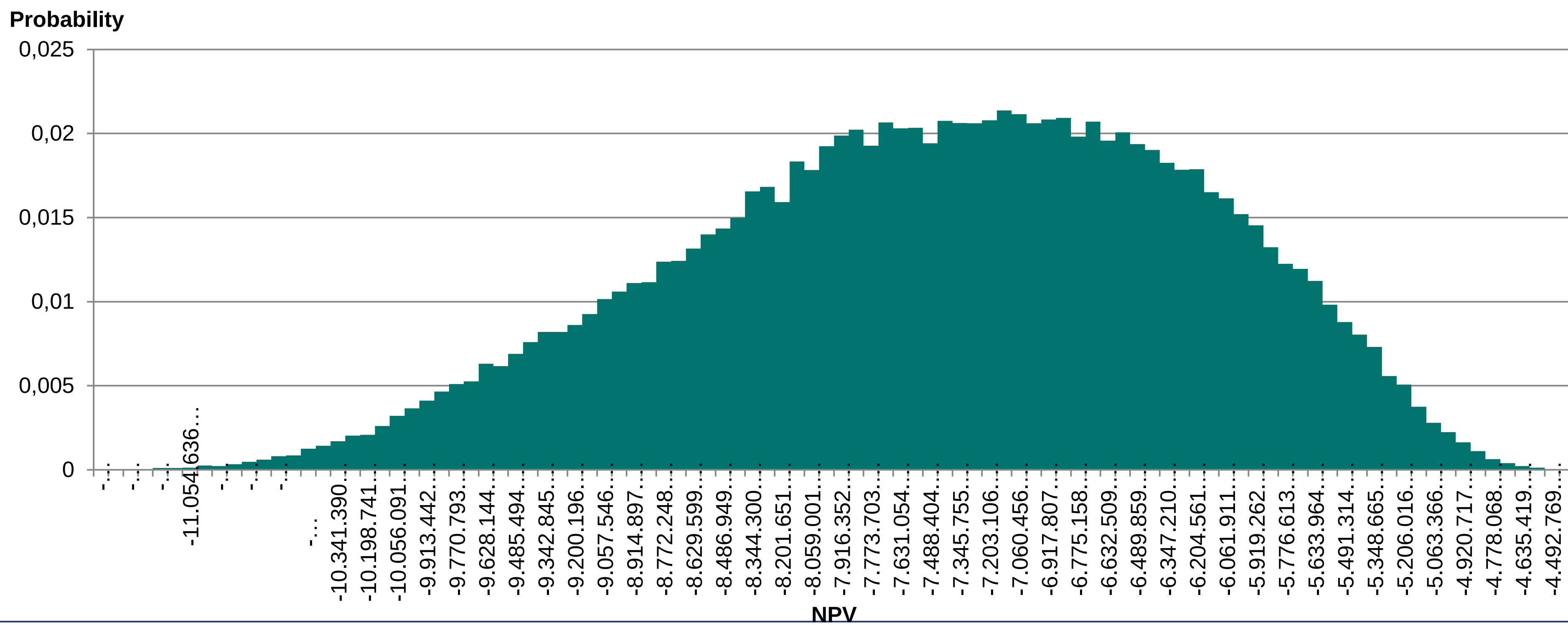
- **Nuclear power is more expensive than competing technologies**
- **Levelized cost of electricity generation:**
  - **11 cent/kWh**

$$\mathrm{NPV}(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

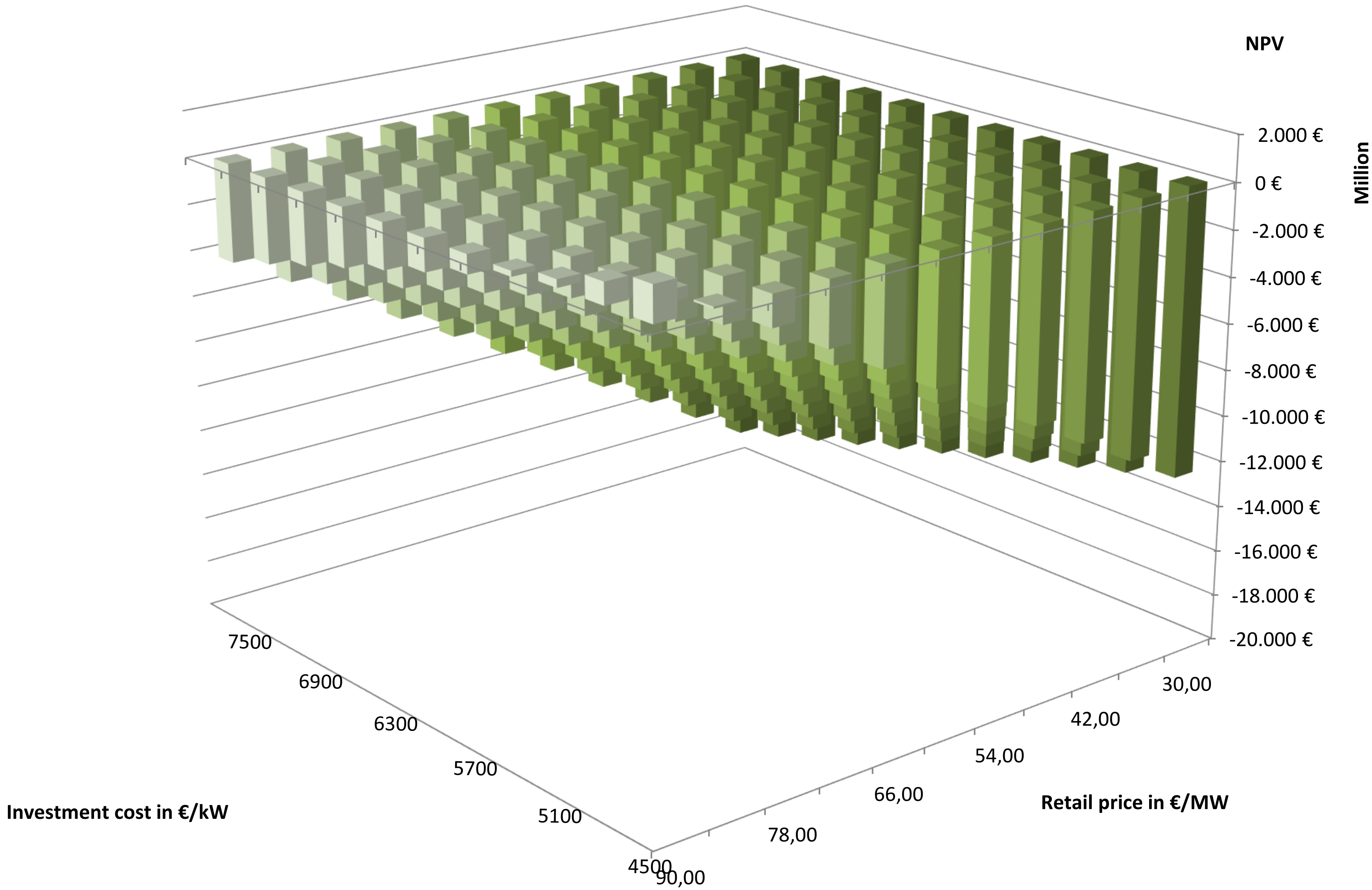
- **Assumed electricity retail price:**
  - **40 €/MWh**
- **Net present value very negative:**
  - **–13 bn €**
- **To reach NPV = 0:**
  - **Retail price: ~100€/MWh**

Nuclear power – profitability check monte carlo analysis

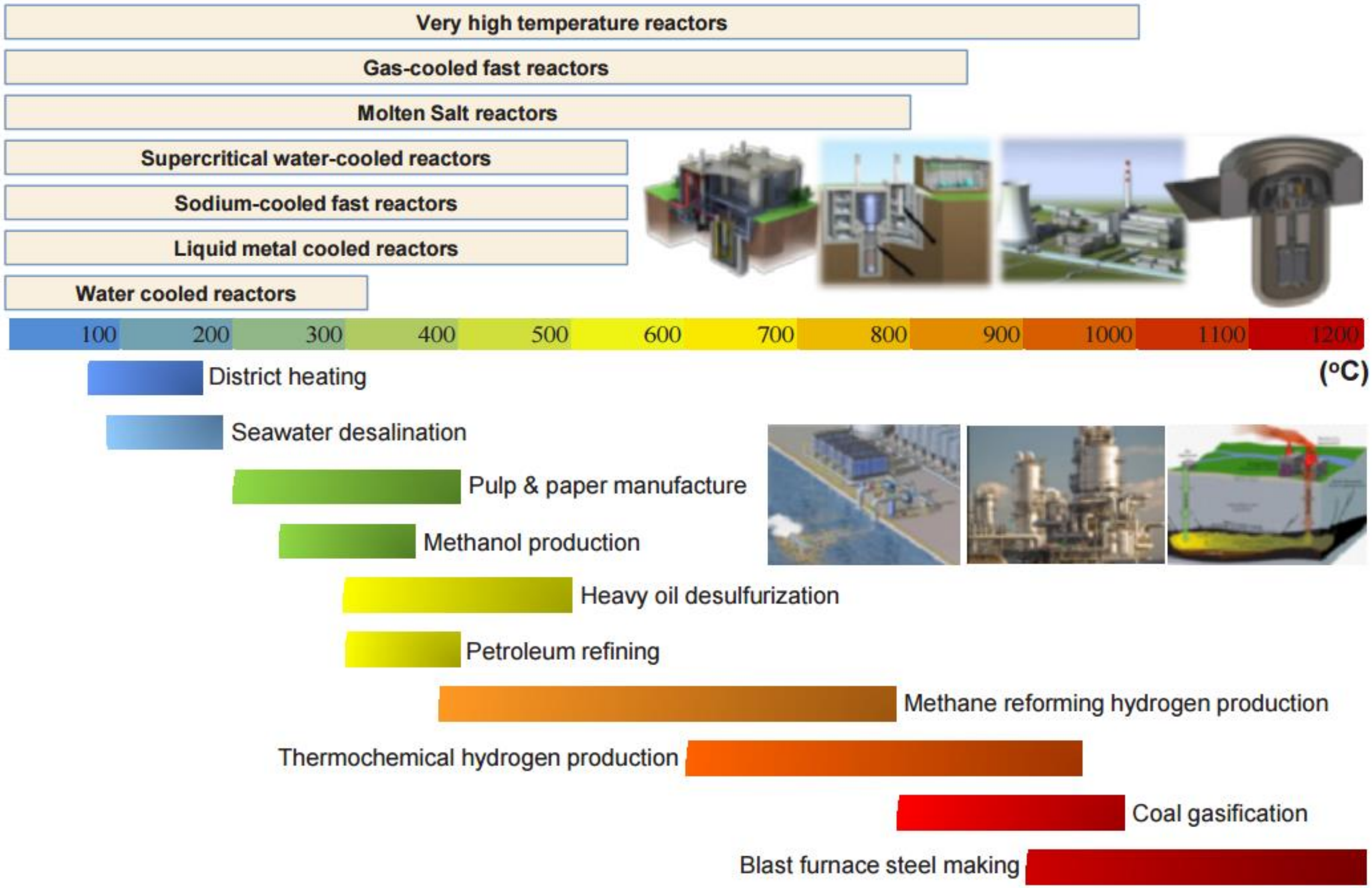
- **Monte carlo parameters**
  - Wholesale electricity price: 30 to 50 €/MWh
  - Investment cost: 4,500 to 7,500 €/kW
  - Debt capital interest rate: 5% to 10%
  - Equity capital interest rate: 2% to 10%
- **Monte carlo results**



Variation of Investment cost and retail price

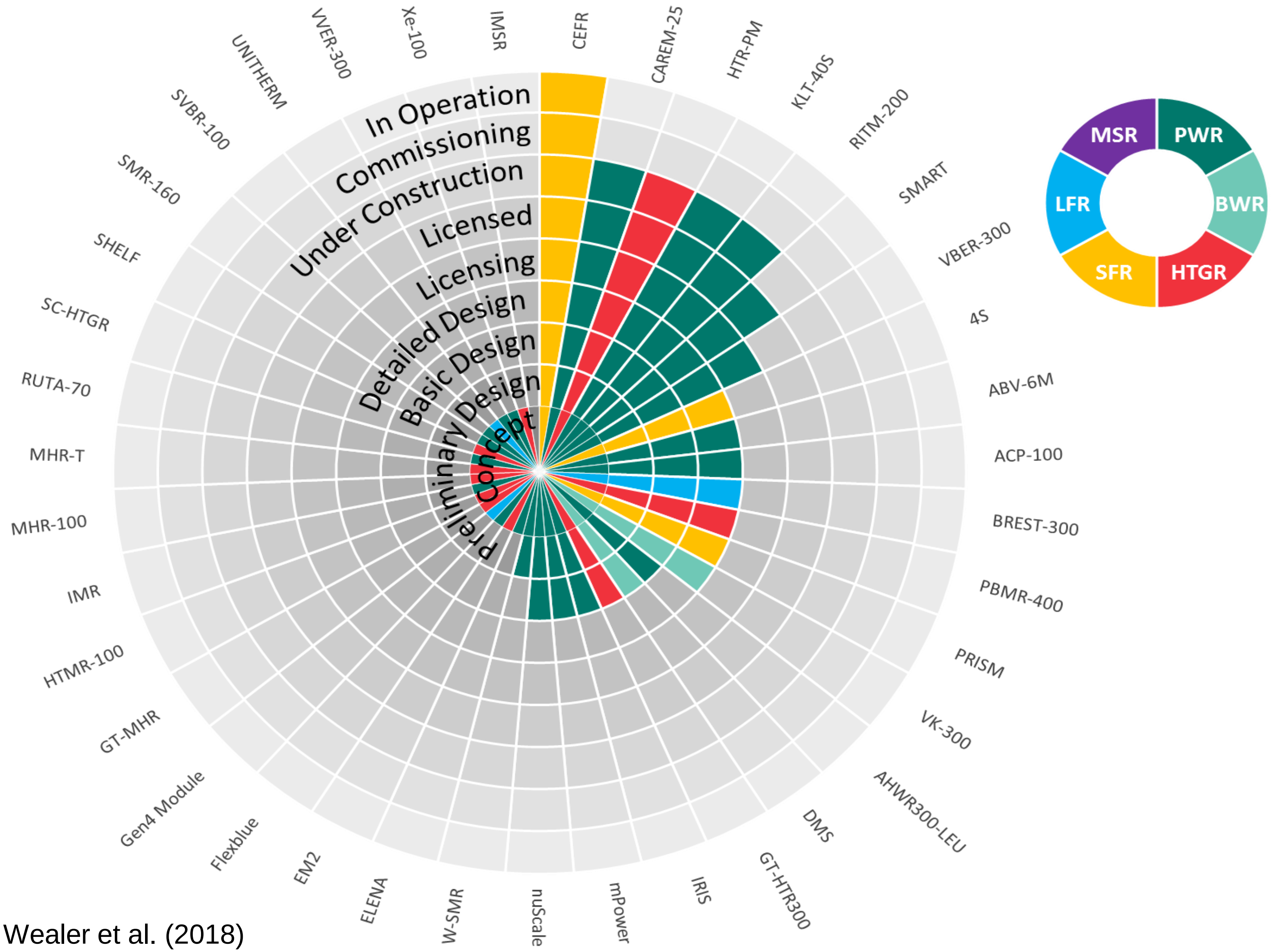


Looking forward…
…Gen IV no option for the foreseeable future (although prototypes exist)



Source: IAEA

…neither are „Small modular reactors“ (SMRs)…



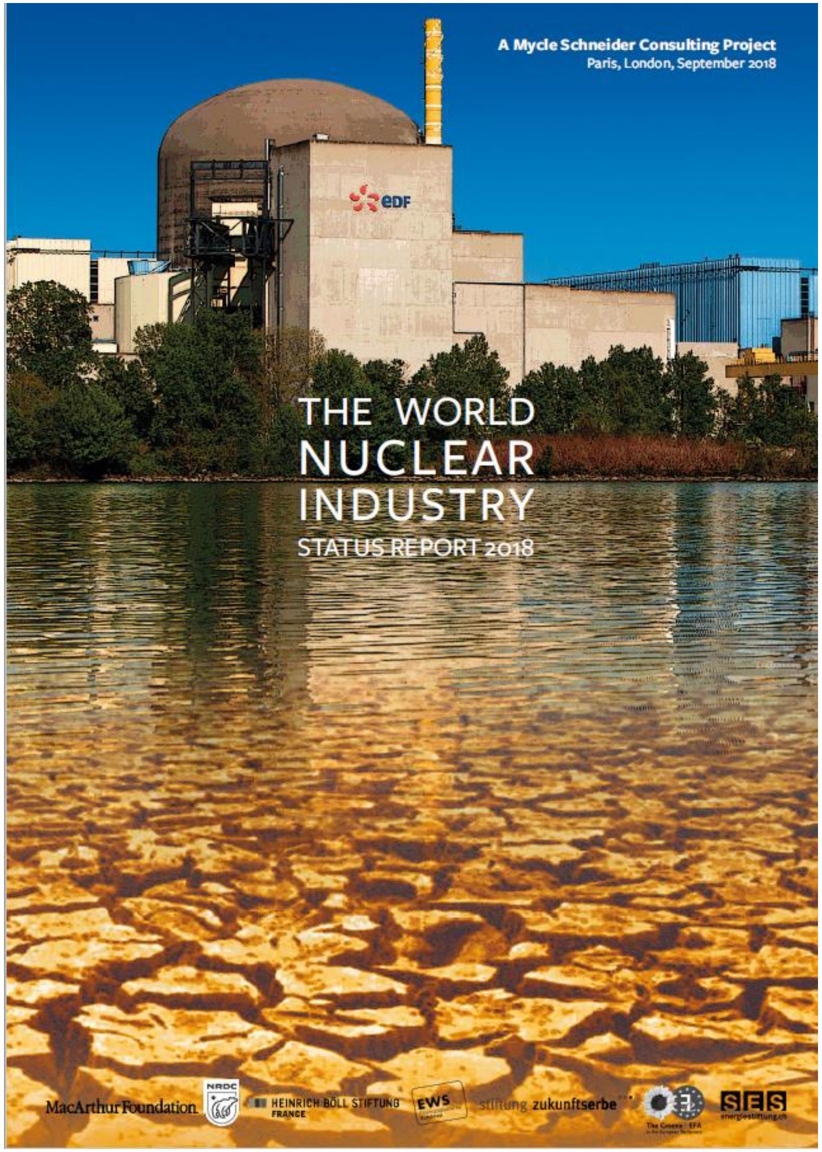
Source: Wealer et al. (2018)

…leading to no short-term prospects for Gen IV and SMRs

- **the concept of SMRs has been around since the dawn of the nuclear age.**
- **No SMR has ever been operated and current projects (if not abandoned) suffer from serious delays – both in construction and reactor design.**
- **In sum, economic viability of SMRs is not clear and <u>no option any private investor</u> would seek; potential scale economies must be weighed against technical risks and higher proliferation risks.**
- **GenIV reactors are only partially based on fundamentally different designs, as FBRs, HTR, thorium concepts are around since the 1950s.**
- **deployment seems far from certain due to even higher capital costs than Gen III+ reactors.**
- **another plea for Gen IV reactors is proliferation resistance, this is not the case, e.g. Gen IV reactors all have a closed fuel cycle, plutonium as fuel…**

Agenda

The Decommissioning Status Report in WNISR (2018)



Since 2018 the World Nuclear Industry Status Report (WNISR) includes a chapter on decommissioning:

"The Decommissioning Status Report"

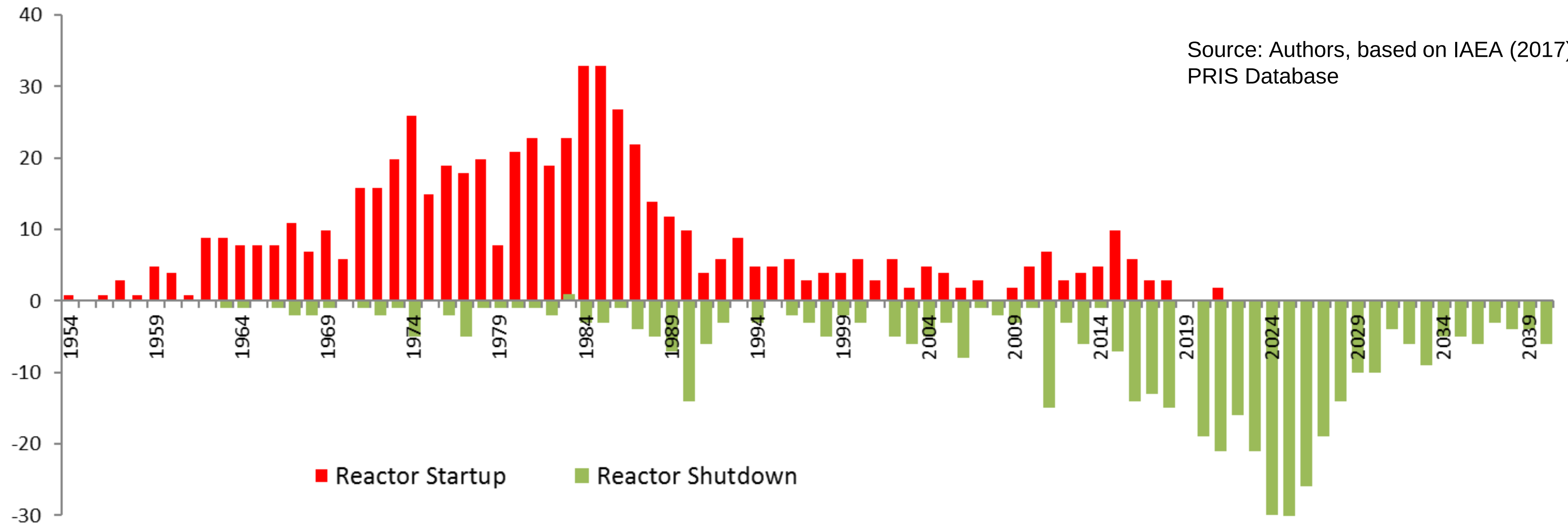
Lead Authors: Mycle Schneider and Antony Froggatt

With: Julie Hazeman, Tadahiro Katsuta, Andy Stirling, Phil Johnstone, M.V. Ramana, Agnès Stienne, Christian von Hirschhausen, and Ben Wealer

The following presentation is largely based on the WNISR (2018).

https://www.worldnuclearreport.org/IMG/pdf/20180902wnisr2018-hr.pdf

Outlook – Global Development of the Nuclear Power Plant Fleet



As of 1 July 2018: 173 permanently shut down reactors, or 74 GW of capacity.

By 2030: a further 216 reactors will shut down (grid connection: 1978-90).

By 2057: additional 111 will be shut down.

Not accounting for 81 operational reactors (grid connection before 1978), and additional 33 reactors in long-term outage (LTO).

IAEA (2004) estimates a 100 US$billion value decommissioning market until 2050

Decommissioning – What Does it Mean?

Decommissioning refers to the ***administrative*** *and* ***technical actions*** *taken to remove all or some of the regulatory controls from an authorized facility so the facility and its site can be reused.* ***Decommissioning includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.*** - IAEA

5-Stage-Classifiaction

1) Peripheral Systems
2) Machinery and higher contaminated parts
3) RPV and biological shield
4) Remaining contaminated systems
5) Greenfield or further proceedings of the building

3-Stage-Classification

- **Warm-up-Stage**: Measures prior to the treatment of the hot zone
- **Hot-zone-Stage**: Removal of the RPV and biological shield
- **Ease-off-Stage**: Measures to release site form regularly control

Source: Wealer et al. (2015)

Standard Procedures of Decommissioning

Warm-up-Stage

- Defueling the reactor
- Overview of all radioactive inventory
- Removal of **peripheral parts and machinery**, that are not needed during the decommissioning phase
- Set up of a technical and logistical **infrastructure for the decommissioning project**

On-site transport of SNF

Image: GSR (2017)

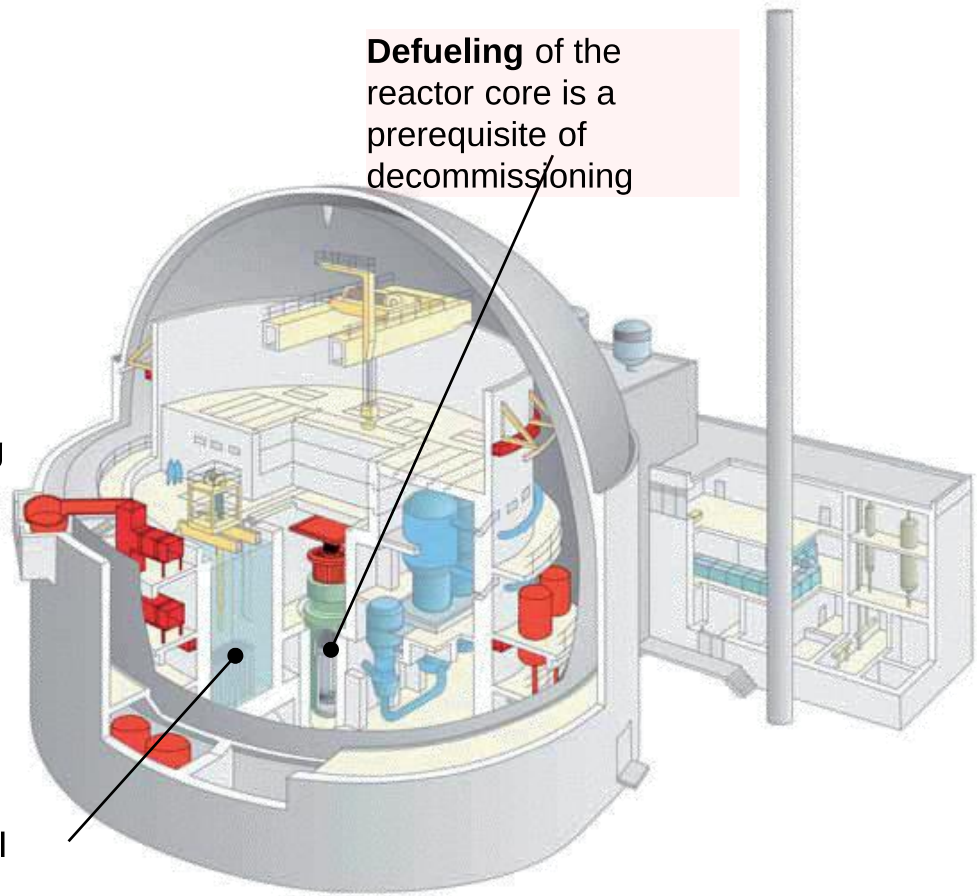


Image: GSR (2017)

Standard Procedures of Decommissioning

Warm-up-Stage

- Deconstruction and dismantling of higher contaminated parts, e.g. the steam generator

Image: GSR (2017)

- Preparations for the dismantling of highly contaminated (or activated), large scale parts

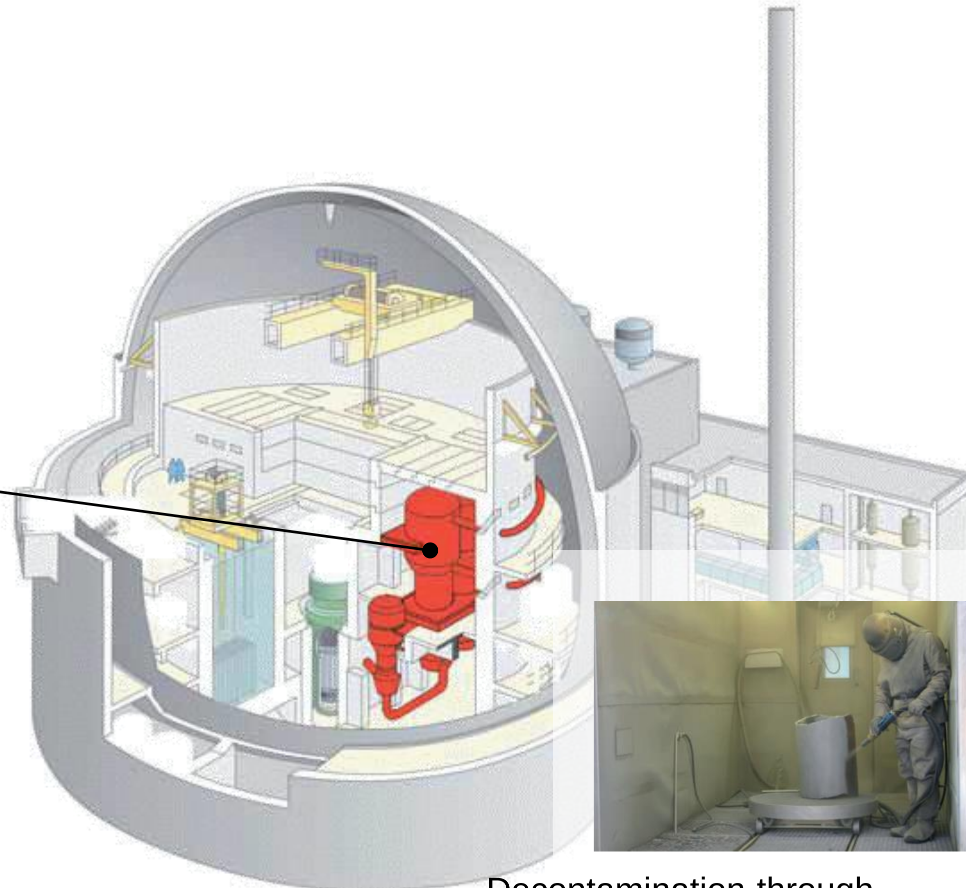
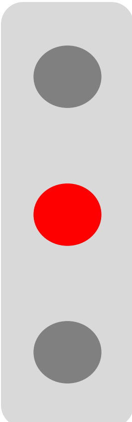


Image: GSR (2017)

Image: GSR (2017)

Decontamination through sandblasting

Standard Procedures of Decommissioning



Hot-Zone-Stage

- Deconstruction and dismantling of **highly contaminated parts e.g. RVP, biological shield**

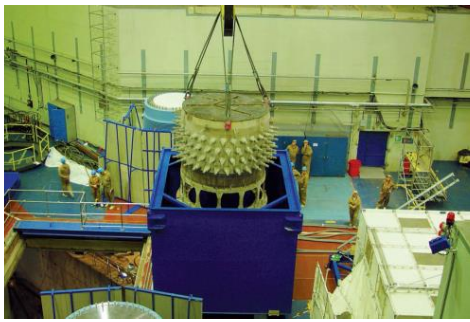
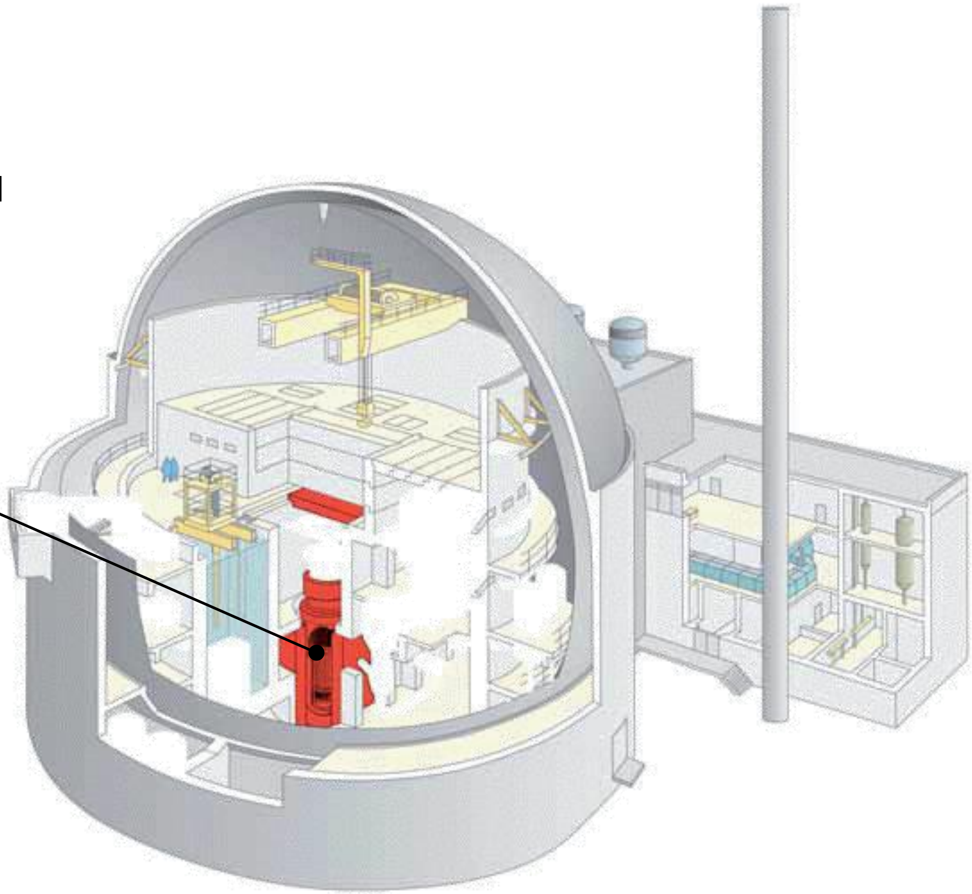
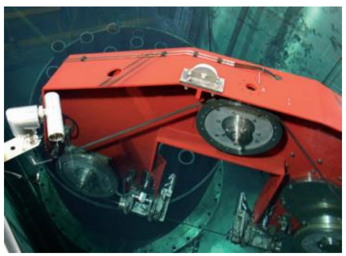


Image: GSR (2017)



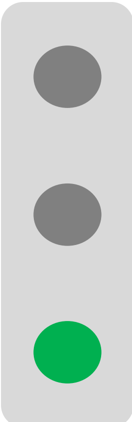
Remote controlled underwater cutting



Images: GSR (2017)

One-piece removal

Standard Procedures of Decommissioning



Ease-off-Stage

- Deconstruction and dismantling **remaining parts and machinery**
- **Decontamination** of the buildings

Image: GSR (2017)

Markings for surface decontamination

- Release from regulatory control

Image: GSR (2017)

Measurements for release

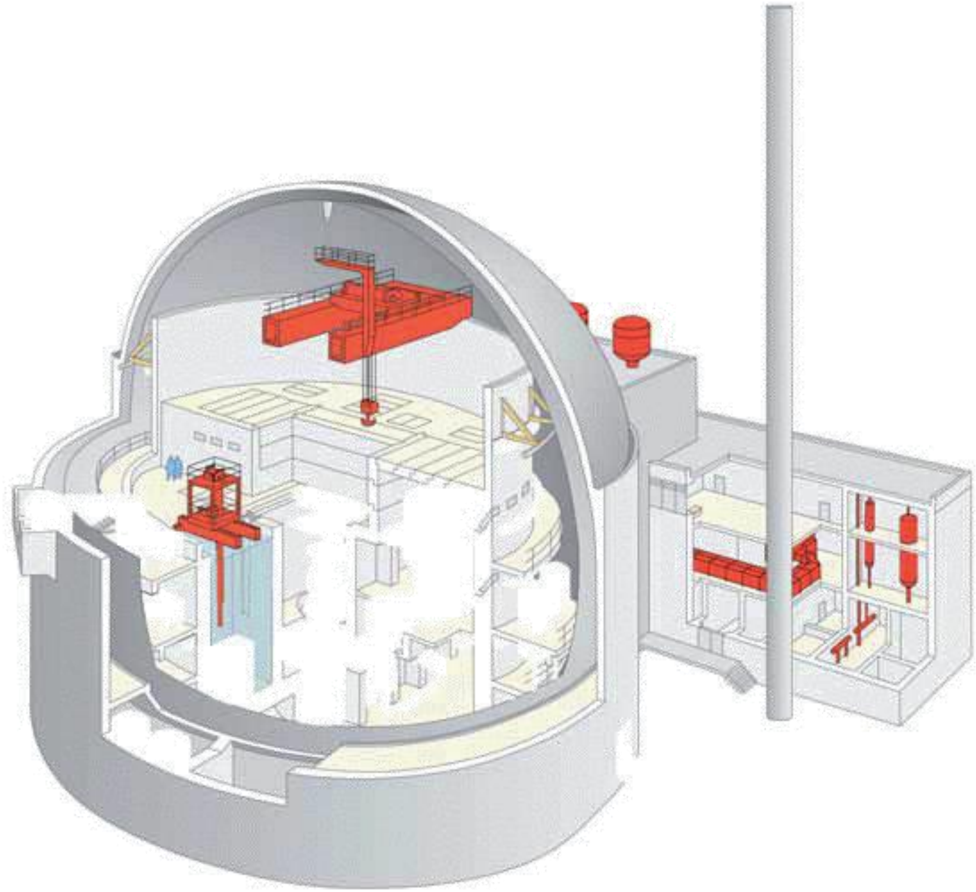


Image: GSR (2017)

Standard Procedures of Decommissioning

Ease-off-Stage

- Demolishing of the buildings
  - **Greenfield**: No further nuclear related purpose of the site
  - **Brownfield**: Further “generation use” (e.g. gas turbine) or further nuclear related uses of the site, e.g. (interim) storage facility for nuclear waste

Images: GSR (2017)

Possible Strategies of Decommissioning

	+	-
IMMEDIATE DISMANTELING (ID)	▪ Skill and expertise of the operating staff is key for decommissioning ▪ Clear line of responsibilities ▪ High public interest ▪ More financial security	▪ High safety precautions due to high intensity of radiation ▪ Larger volumes of radioactive waste ▪ Lack of motivation of the workforce
LONG TERM ENCLOSURE (LTE) or DEFERRED DISMANTLING (DD)	▪ Lower intensity of radiation due to radioactive decay ▪ Possibility to raise more decommission funding during the period of enclosure ▪ Possibility to co-ordinate the decom. of different units in multiple plants	▪ Risk of losing – trained staff and knowledge about the facility – clear lines of responsibilities – public interest ▪ Risk of bankruptcy or other financial trouble of the company in charge
ENTOMBMENT	▪ Relatively easy to realize	▪ *Out of sight, out of mind:* no dismantling of the reactor ▪ Unpredictable risks ▪ Constant occupation over a long period requires staff and financial stamina

Organizational models for decommissioning (and radioactive waste management)

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)

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Global Survey

In the first quarter of 2018 154 units were globally undergoing (in various stages) or awaiting decommissioning.

D&D of the 19 NPPs (6 GW) was completed on average 16 years after shutdown.

Only 10 sites have been returned to a greenfield.

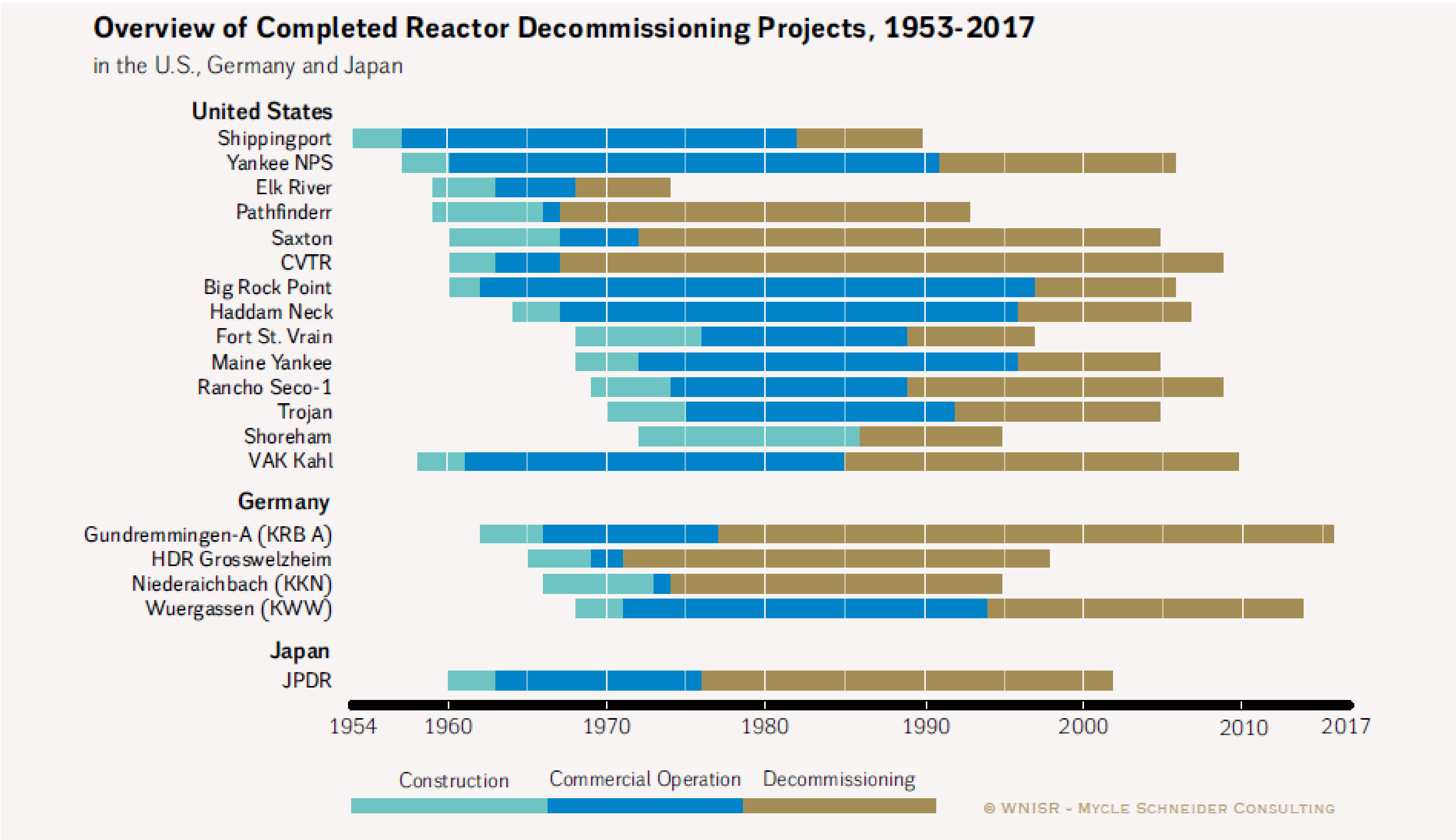
The only countries to have completed the decommissioning process are the United States (13), Germany (5), and Japan (1).

Country	Shut-down 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	20 3[a]	0	0	0	1 [4%]
United Kingdom	30	0	0	0	30	0
United States	34	4	0	5	124	13 [38%]
Total	136	37	5	13	58	19

a - Not including the Fukushima Daini 1-4 reactors.

Sources: Various, compiled by WNISR, 2018

Overview of Completed Decommissioning Projects, 1953 - 2017



Source: WNISR and IAEA-PRIS, 2018

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Key Findings in France

12 reactors (8 GCR UNGG, 1 HWGCR, 2 FBR, 1 PWR) were shut down.

While EDF operates 57 PWRs (1 in LTO), the legacy fleet consists mainly of GCRs.

French Regulation stipulates Immediate Dismantling (ID).

EDF's strategy shift in 2016: Decommissioning start of the first GCR Chinon A-1 in 2031 as an example for future GCR projects. LTE is de facto applied for 6 GCRs to await decommissioning.

In addition, there is not even a theoretical disposal route for graphite.

Only one PWR (Chooz-A) undergoing decommissioning. Since 2014, first underwater dismantling of an RPV.

9 reactors are the scope of EDF, 3 CEA.

Decommissioning monies are managed in internal segregated funds.

France	May 2018
"Warm-up-stage"	3
of which defueled	2
"Hot-zone-stage"	1
"Ease-off-stage"	0
LTE	8
Finished	0
of which greenfield	0
Shut-down reactors	**12**

Sources: Various, compiled by WNISR 2018

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

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

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Key Findings in the United States of America

Operators can chose ID, LTE (up to 60 years), or Entombment.

Average decommissioning period of 14 years. 8 reactors were decommissioned under 10 years (removal of RPV as whole).

Strategy to remove large components in one piece in the Hot-Zone.

Possible use of explosives to demolish concrete buildings.

High cost variance: US$280/kW (Trojan) to US$1,500/kW (Connecticut Yankee)

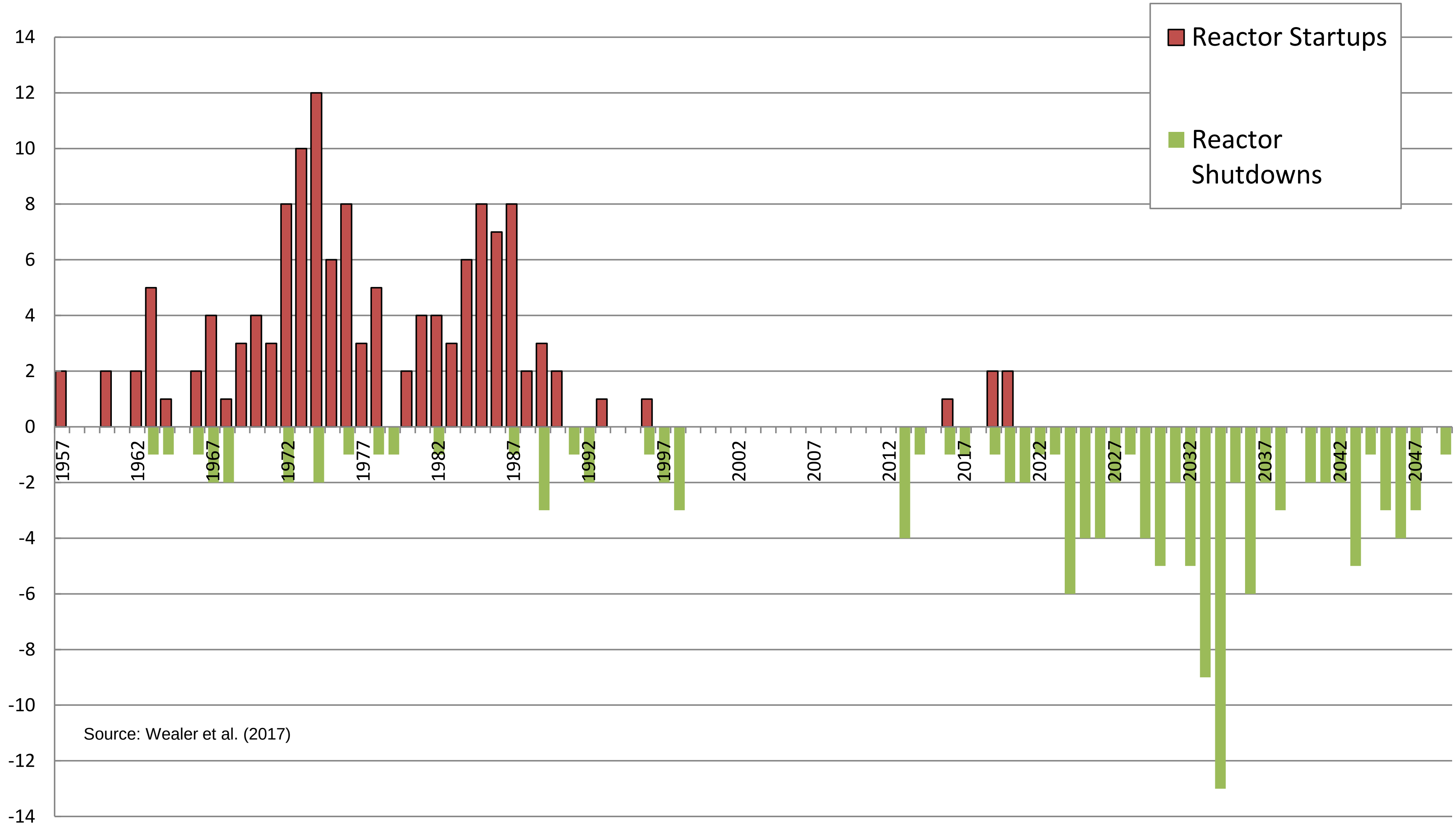
External segregated fund (Nuclear Decommissioning Trust Fund): USD 64 billion in 2016.

The site license might be reduced to the Independent Spent Fuel Storage Installation.

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

Source: WNISR (2018)

US nuclear power reactor grid connections and permanent shutdowns (1957 – 2050)



New development: transfer decommissioning license from the operator to a waste management company

Zion-1 and -2 in Illinois: Exelon transferred the license to EnergySolutions.

Goal: reap efficiency gains through the (co-)management of the decommissioning process by a company owning disposal facilities.

Vermont Yankee: U.S. company Northstar has entered into a purchase and sale agreement with Entergy. The deal would include the transfer of the decommissioning trust of US$571 million (Entergy has promised to add another US$125 million). Entergy and Northstar are proposing this model also for the Pilgrim, Indian Point and Palisades stations.

These developments are problematic as limited-liability companies are only financially liable in the case of an accident or other legal dispute up to the value of their assets.

Therefore, if the decommissioning funds are exhausted, such a third-party company could declare bankruptcy, leaving the bill for the taxpayer.

Overall, there is an increasing risk, that the NDT will not be sufficient to cover the costs (outdated NRC-formula based on studies between 1978 and 1980).

Agenda

Key Findings in Germany

Immediate Dismantling was the most applied strategy - now set by law.

EUR 6.5 billion bill for the state only for the decommissioning of the 6 Soviet reactors of the former GDR (currently in EOS but deferred dismantling).

EUR 19.7 billion estimated costs for decommissioning in 2014 set aside in internal non-segregated funds.

The utilities are still responsible for decommissioning and for the conditioning of waste, but all the downstream tasks (mainly storage) will be done by public companies and paid from the waste fund.

Only 3 reactors (140 MW) have been released from regulatory control.

Gundremmingen-A (2.2bn latest cost est.) and Würgassen (1bn €) de facto decommissioned.

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**

Source: Seidel and Wealer, 2016 and Bredberg, et al. 2017[519]

Organizational Challenges: Oligopoly, further delays very likely

Germany is currently exploring large-scale decommissioning. The work is carried out by the utilities while some works are tendered to specialized companies.

Wealer et al. (2015) suggest a potential oligopoly and the potential abuse of market power due to market concentration. Some solidification for this suggestion could have been observed in 2018: PreussenElektra awarded the dismantling of the RVI of six plants to a consortium led by waste management company GNS and Westinghouse. GNS is utilities-owned with PreussenElektra being the major shareholder with 48 percent of the shares.

Possible economies of scale with WH/GNS decommissioning six NPPs.

Only one of the 8 reactors shut down after Fukushima has been defueled: The special fuel rods of Brunsbüttel were sent to Sweden and are thought to be sold to the US.

Insufficient number of storage and transport casks for SNF, while casks for the special fuel rods are still missing.

Agenda

1) Introduction
2) Nuclear Power Economics
3) Decommissioning of Nuclear Power
    1) Global Survey
    2) France
    3) United States of America
    4) Germany
    5) **Japan**
4) Conclusion and Outlook

Key Findings in Japan

No valuable experience with decommissioning yet.

The Fukushima Accident (March 2011) caused serious trouble to the internal decommissioning funds of the operator. A strategy of Safe Storage of approx. 10 years is likely to be applied for the majority of the reactors.

Reactors can receive a unique lifetime extension of 20 years under the revised regulation (induced by the investigations of the Fukushima accident).

Full market liberalization in 2016 makes the accumulation of decommissioning funds even more difficult.

Estimated costs appear moderate and affordable but are subjected to uncertainties due to lack of experience.

For some reactors the restart option might be even more expensive than the shutdown.

Japan	May 2018
"Warm-up-stage"	20
of which defueled	*1*
"Hot-zone-stage"	0
"Ease-off-stage"	0
LTE	0
Finished	1
of which greenfield	*1*
Shut-down reactors	**25**

Organizational Challenges: Underprovisioning, Fukushima

Historically, electric utilities had to establish tangible fixed assets for the expenses of decommissioning during the period of operation through surcharges on the retail price of electricity and based on the output of a facility.

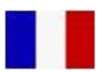
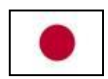
Since 3/11: total decommissioning costs are allocated by the straight-line method over the period of operation and safe storage and the surcharges were decoupled from the electricity output of a reactor.

To cover the financial shortage, many operators chose the strategy of intermediate storage (5-10 years) for their reactors in order to collect more money.

In 2015, METI estimated an average of ¥71.6 billion per reactor but more recent estimates for the five latest reactors slated for decommissioning were significantly raised to ¥160 billion (US$1.46 billion) per reactor.

Another issue for the decommissioning process in Japan is that companies are permitted to temporarily divert decommissioning funds for other business purposes and thus risking that the funds are not available when needed.

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	 EWN  Magnox Sellafield Ltd			
2) External segregated fund		 EDF 		
3) Internal non segregated fund				
4) Internal segregated fund	 	 		
5) Further Alternatives				

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

Agenda

1) Introduction
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Decommissioning is technologically and financially challenging

The country case studies also suggest that both, duration and costs have been largely underestimated. The few projects that have started encounter, in nearly all the cases, delays as well as cost increases.

Japan will enter a difficult phase in the near future—as the first reactor pressure vessel of a commercial reactor has to be removed yet.

The U.S. have decommissioned the highest number of reactors (13), but these case studies cannot be used as a reference for other cases, e.g. the removal and consequent burial of large-scale parts.

In all the cases, interim storage facilities were needed, hindering decommissioning or even rendering the regulatory release of the site impossible.

The early nuclear states UK, France, and Canada have not fully decommissioned a single reactor.

In addition, going forward, decommissioning faces a challenge in a context of low electricity prices placing a further strain on the competitiveness of nuclear power plants—and low provisions on behalf of the companies.

NPP decommissioning is outpacing new-build

Investment costs for NPPs have significantly increased in the western hemisphere over the last decades

Due to increased market competition and the disappearance of large vertically integrated utilities, there is no guarantee that market prices will be high enough to cover costs, e.g., investment and interest costs.

Traditional reactor vendors: in financial troubles and tainted technologies

Until now no NPP was built under what is generally considered "economic" grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system

If Russia and China are able to provide the role of a global supplier needs to be seen, but both countries provide a strong government backed package including financing as a policy tool.

In mid-2018, a total of 115 NPPS were being decommissioned, while only 50 NPPS were being built worldwide.

Thank you for your attention!

Contact:

bw@wip.tu-berlin.de

Backup

Last but not least: the role of government for newbuild

Today, no privately run energy conglomerate risks building a nuclear power station without government subsidies and guarantees. It is noticeable that new nuclear power stations are built particularly where the government and the energy industry form an unholy alliance."

Ralf Fücks in the preface for Thomas (2010a): The economics of nuclear power – An update.

Reactors currently under construction and their financing mechanisms, as of 5 March 2017.

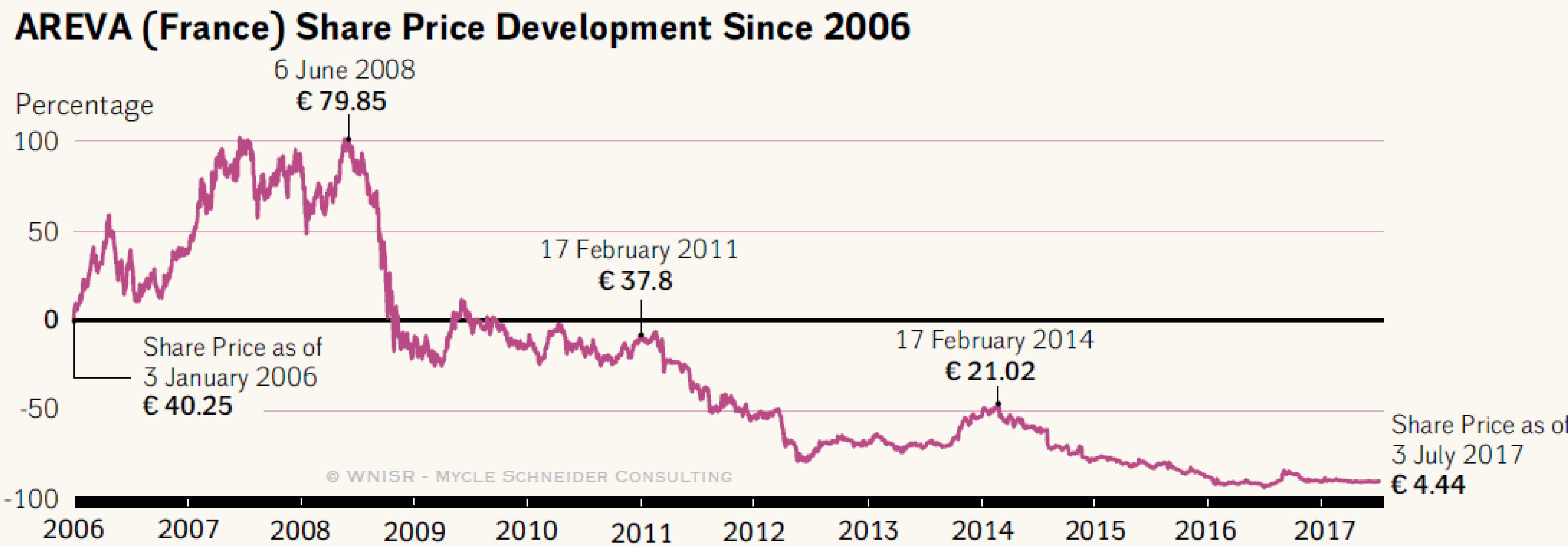
Country	Units	MWe (net)	Construction Start	Financing Type/Model
China	22	20,500	2009–2015	Government/Vendor
Russia	7	5520	1983–2010	Government
India	5	2990	2002–2011	Government/Vendor
USA	4	4468	1972–2013	Government/Private sector
UAE	4	5380	2012–2016	Government/Vendor
South Korea	3	4020	2008–2013	Government
Pakistan	3	2343	2011	Government/Vendor
Belarus	2	2218	2013–2014	Government/Vendor
Japan	2	2683	2007–2010	Government/Other
Slovakia	2	880	1985	Government/Corporate Finance
Ukraine	2	2068	1986–1987	In process
Argentina	1	25	2014	Government
Brazil	1	1245	2010	Government/Vendor
Finland	1	1600	2005	Government/corporate Finance/Project Finance (Mankala Model)
France	1	1600	2007	Corporate Finance

Source: IAEA-PRIS for construction data. The data on financing mechanism are from various publications, World Nuclear News, Nucleonics, Reuters, WNA country profiles, and authors' opinion

Source: Barkatullah and Ahmad (2017, 130).

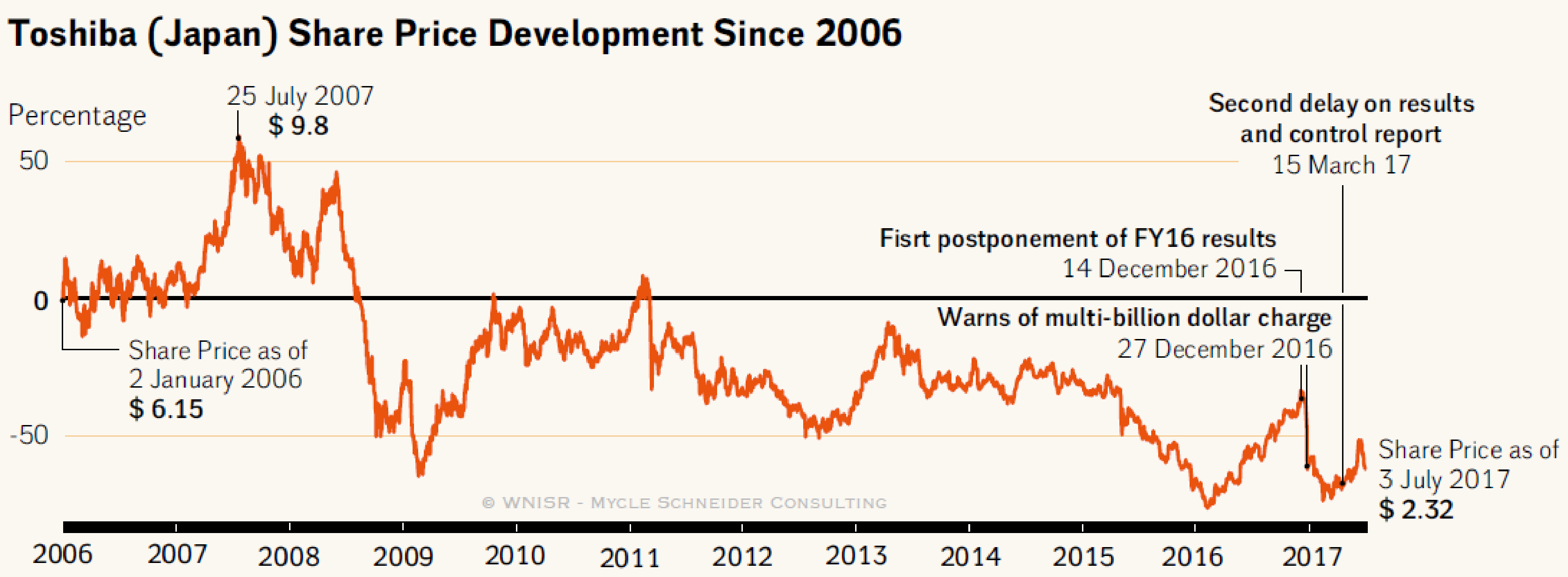
- **Hinkley Point C: contract for difference, guaranteed price of £92.50/MWh over the first 35 years**
- **Olkiluoto-3: fixed price contract**

Figure 30 | AREVA Share Price Development Since 2006



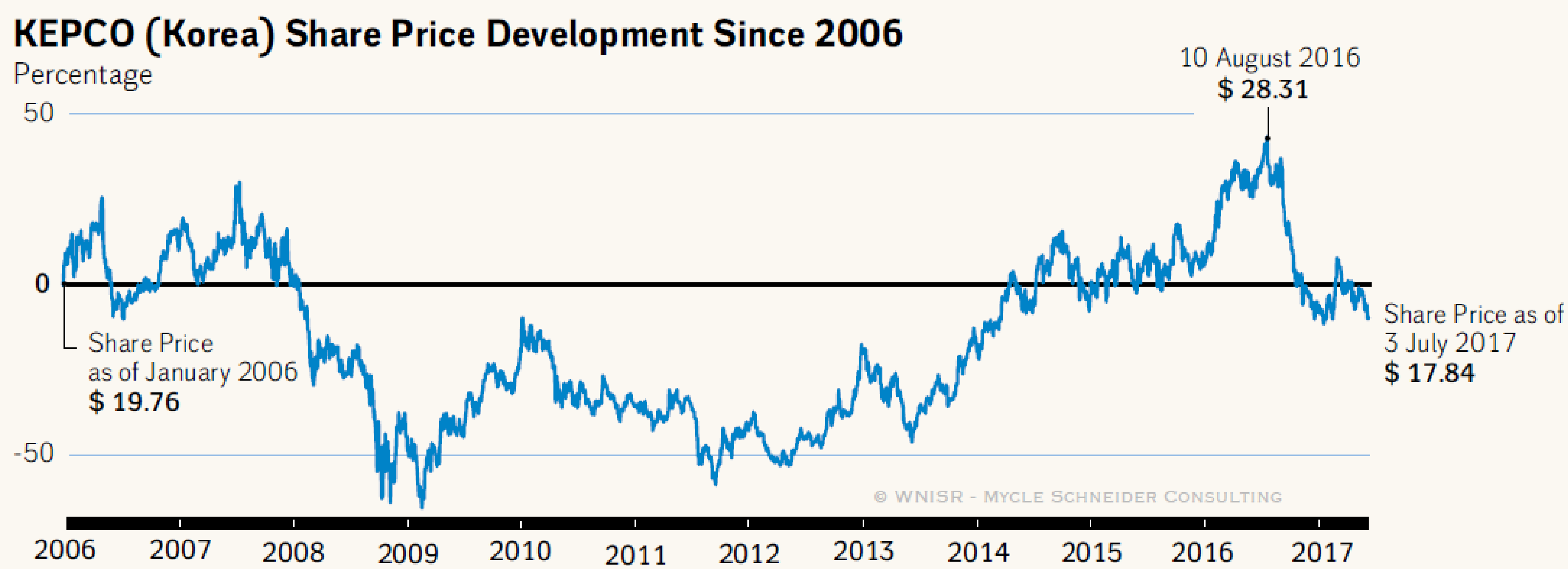
Source: Investing.com, August 2017

Figure 34 | Toshiba Share Price Development Since 2006



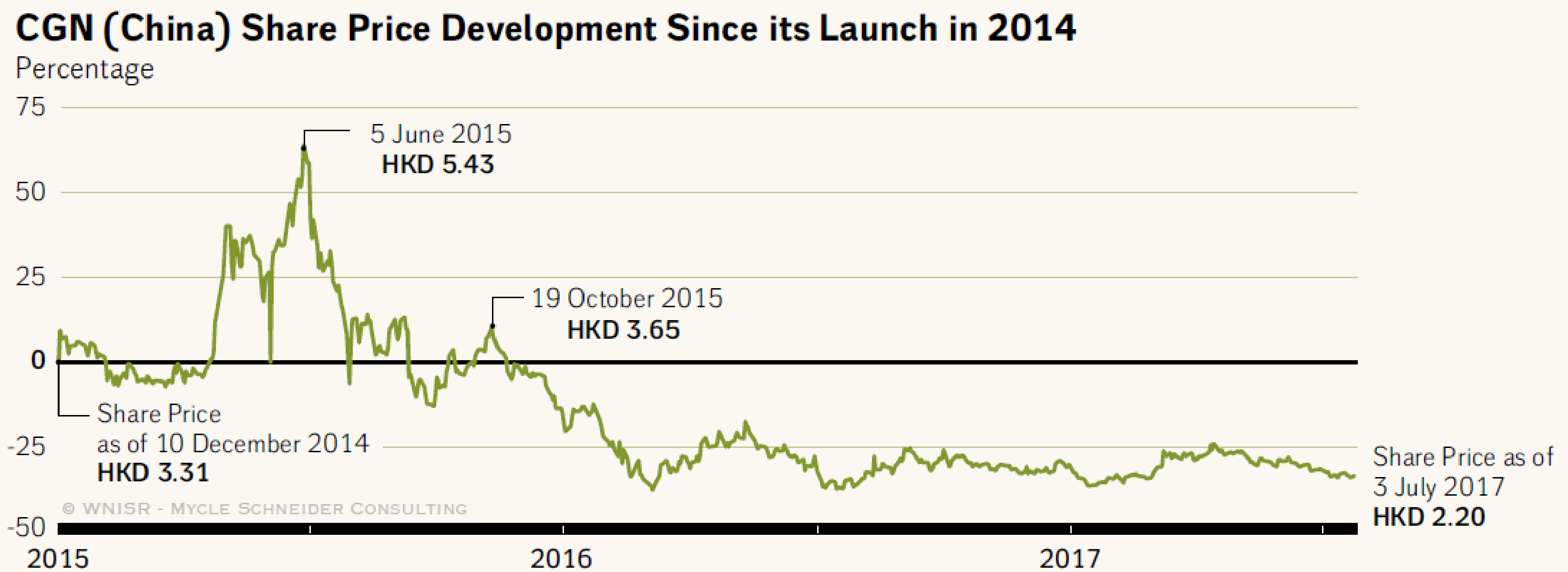
Source: Yahoo Finance, August 2017

Figure 35 | Kepco Share Price Development Since 2006



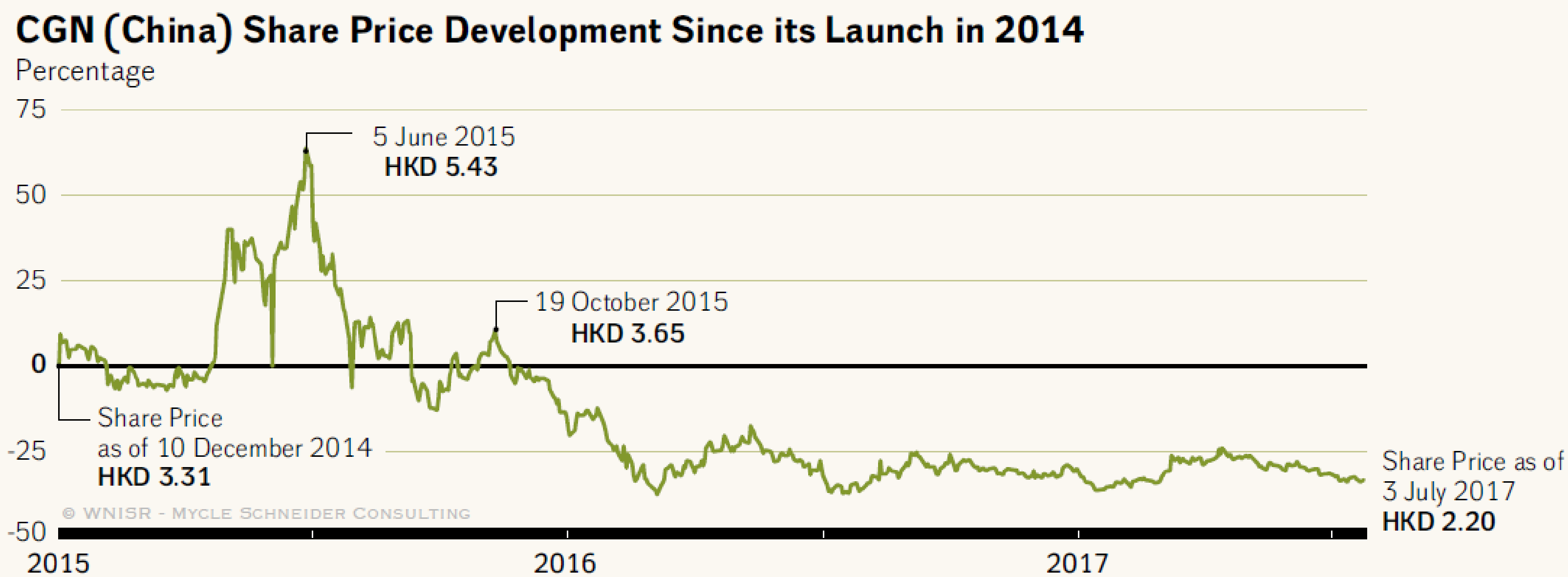
Source: Yahoo Finance, August 2017

Figure 36 | CGN Share Price Development Since its Launch in 2014



Source: Yahoo Finance, August 2017

Figure 36 | CGN Share Price Development Since its Launch in 2014



Source: Yahoo Finance, August 2017

Monte-Carlo Simulation: Costs and parameters

- Fixed and variable costs of nuclear power
  - Operating costs (fixed):
    - Operation 20 €/installed kW/year
    - Maintenance 20 €/installed kW/year
    - Insurance 15 €/installed kW/year

  - Operating costs (Variable):
    - Operation 8 €/MWh_el
    - Maintenance 7 €/MWh_el
- Parameters
  - Market Variables:
    - Wholesale Electricity Base Price
    - Wholesale Electricity Peak Price

  - Power Plant Variables:
    - CO2 Price
    - Max. CO2 Price
    - Fuel Price
    - Installed Capacity (electrical)
    - Specific Investement Costs
    - Electric Efficiency
    - Load Hours

Source: Schröder et al. (2013)

Germany: Decommissioning status I/II

8 commercial power reactors with running or terminated decommissioning process

Reactor design	NPP	Shut-down	Reactor Model [MW]	Operator/Owner	Current Status	Begin of decommissioning	Planned termination	Costs [million EUR]
BWR	Lingen	1977	1. Gen [183 MW]	RWE	LTE, 2015: license granted	-	-	-
	Gundremmingen A	1977	1. Gen [237 MW]	75% RWE; 25% E.ON	Stage 4	1983	-	2,200
	Würgassen	1994	1. Gen [640 MW]	E.ON	completed	1997	2014	1,000
PWR	Mülheim-Kärlich	1988	Konvoi [1,219 MW]	RWE	Stage 3	2004	2021	725
	Greifswald 1-5	1989/90	4 x VVER V-230, 1 x V-213 [4 x 408 MW]	Energiewerke Nord GmbH	Stage 4	1995	-	6,500
	Rheinsberg	1990	VVER-70 [62 MW]	Energiewerke Nord GmbH	Stage 4	1995	2069	
	Stade	2003	1. Gen [640 MW]	66,7% E.ON; 33,3% VENE GmbH	Stage 4	2005	2015	500
	Obrigheim	2005	1. Gen [340 MW]	EnBW	Stage 4	2008	2020 -2025	600

Source: updated Wealer et al. (2015)

- Terminated decommissioning projects: HDR Grosswelzheim (25 MW) (1988-1998), Kernkraftwerk Niederaichbach (110 MW) (1987-1995), VAK Kahl (1988-2010) (15 MW).
- Other NPPs in decommissioning process:, MZFR Karlsruhe (57 MW) (Stage 4), THTR-300 (LE) (296 MW), AVR Juelich (2003, Stage 3) (13 MW), KNK II (21 MW) (1993, Stage 3)

Germany: Decommissioning status I/II

9 NPPs in post operation and Gundremmingen B (closes in 2017)

Reactor design	NPP	Operator	Reactor Model [MW]	FE	SFR	Defuelling ends in	Beginn of D&D	Estim. D&D duration
BWR	Brunsbüttel*	66.6% VENE; 33,3% E.ON	BWR-69 [771 MW]	517	12	2017 (ended)	2017	10-15 years
	Gundremmingen B	75% RWE; 25% E.ON	BWR-72 [1,284 MW]	3008		-	-	-
	Isar 1	E.ON	BWR-69 [878 MW]	1734	44	2018	2017	10 years
	Krümmel	50% VENE; 50% E.ON	BWR-69 [1,346 MW]	1094	62	-	2019/2020	10-15 years
	Philippsburg 1	98,45% EnBW	BWR-69 [890 MW]	886	29	2017	-	15 - 20 years
PWR	Biblis A	RWE	2. Gen [1,167 MW]	440	59	2016	2017	15 years
	Biblis B	RWE	2. Gen [1,240 MW]	506	235	2017	2017	15 years
	Grafenrheinfeld	E.ON	Vor-Konvoi [1,275 MW]	597		-	-	-
	Neckarwestheim 1	98,45% EnBW	2. Gen [785 MW]	347	84	2017	2017	15 years
	Unterweser	E.ON	2. Gen [][1,345 MW]	413	77	2019/2020	-	until 2025

Source: updated Wealer et al. (2015)

* Vattenfall awarded the contract to dismantle the RVI to Areva-EWN joint-venture in 2017

France: Decommissioning status for EDF's legacy fleet

Reactor design	NPP	Reactor model [MW]	Operating Time	Current Stage	Initial End of Decommissioning	End of Decommissioning	Cost estimations [million EUR]
Other	EL-4 (Brennilis)	HWGCR [70 MW]	1968 – 1985	Partial dismanlting	2015	2028 (estimated)	458.6
	Super -Phenix (Creys-Malville)	FBR – Na-1200 [1.200 MW]	1986 - 1998	Stage 3		2026	1,311.5
PWR	Chooz – A	PWR [305 MW]	1967 – 1991	Stage 3	2016	2025	344.4
GCR	Bugey-1	GCR – UNGG [540 MW]	1972 – 1994	LTE	2026	22nd century	585.9
	Chinon A-1	GCR – UNGG [540 MW]	1964 – 1973	LTE	2031	2056	930.3
	Chinon A-2	GCR – UNGG [540 MW]	1965 – 1985	LTE	2034	22nd century	
	Chinon A-3	GCR – UNGG [540 MW]	1966 – 1990	LTE	2035	22nd century	
	St. Laurent A-1	GCR – UNGG [390 MW]	1969 – 1990	LTE	2031	22nd century	997.6
	St. Laurent A-2	GCR – UNGG [465 MW]	1971 – 1992	LTE	2036	22nd century	

Source: Wealer and Seidel (2016), Cour des Comptes (2014)

- First GCR reactor dismantling approx. 2031-2056
- Chooz-A Stage 3 executed by Westinghouse
- cost estimates, based on contractor quotes

Decommissioning monitoring for United Kingdom

Reactor concept	Site	Reactor type	Operating time	Strategy	SLC	License terminates in
GCR	Berkeley	Magnox [2x 138 MW]	1962 – 1988/89	LTE	Magnox Ltd	2083
	Bradwell	Magnox [2x 123 MW]	1962 – 2002	LTE	Magnox Ltd	2104
	Chapelcross	Magnox [4x 48 MW]	1959/60 -2004	LTE	Magnox Ltd	2128
	Dungeness A	Magnox [2x 225 MW]	1965 – 2006	LTE	Magnox Ltd	2111
	Hinkley Point A	Magnox [2x 235 MW]	1965 – 2000	LTE	Magnox Ltd	2104
	Hunterston A	Magnox [2x 150 MW]	1964 – 1989/90	LTE	Magnox Ltd	2090
	Oldbury A	Magnox [2x 217 MW]	1967/68 – 2011/12	LTE	Magnox Ltd	2106
	Sizewell A	Magnox [2x 210 MW]	1966 – 2006	LTE	Magnox Ltd	2110
	Trawsfynydd	Magnox [2x 195 MW]	1965 - 1991	LTE	Magnox Ltd	2098
	Wylfa	Magnox [2x 490 MW]	1971/72 – 2012/15	LTE	Magnox Ltd	2106
	Windscale AGR	AGR [24 MW]	1963 – 1981	LTE	Sellafield Ltd	2120
	Calder Hall	Magnox [4x 49 MW]	1956/59 – 2003	LTE	Sellafield Ltd	2120
Other	Dounreay PFR	FBR [234 MW]	1976 – 1994	LTE	DSRL	2333
	Dounreay DFR	FBR [11 MW]	1962 – 1977	LTE	DSRL	2333
	Winfrith SGHWR	SGHWR [92 MW]	1968 - 1990	LTE	Magnox Ltd	2019

The inseparable nexus: nuclear power and nuclear weapons

- Acheson-Lilienthal Report (1946, p.10): *"The development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent."*

- Lovins et al. (1980, p. 1144):
    - "*The propagation of nuclear power thus turns out to have embodied the illusion that we can split the atom into two roles as easily and irrevocably as into two parts—forgetting that atomic energy is a-tomic, indivisible.*

- Hirschhausen (2017): interpretation of the nuclear industry in terms of "economies of scope", where strategies, costs, and benefits must be assessed in the multiproduct context of military and civilian uses of nuclear power.

The perspectives of nuclear power

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No Scope countries	Scope countries“	Newcomer countries
Germany, Spain, Belgium, Italy, Switzerland, Sweden, South Korea ➔ Close down NPPs, currently no replacement foreseeable What about Japan, Eastern Europe?	USA, UK, India, Pakistan, France, North Korea, Russia, China ➔ Scope countries call for future nuclear deployment, heavy investments into the nuclear supply chain, and retrofitting of older nuclear plants.	Iran, UAE, Turkey, Saudi Arabia, Egypt, Jordan, Bangladesh, Sudan, Belarus ➔ High dynamics especially in the Middle East: if Iran wants reprocessing, Saudi Arabia will want it too

Conclusion: Nuclear power is not competitive

- **Investment costs for NPPs have significantly increased in the western hemisphere over the last decades**
- **Due to increased market competition and the disappearance of large vertically integrated utilities, there is no guarantee that market prices will be high enough to cover costs, e.g., investment and interest costs.**
- **Traditional reactor vendors: in financial troubles and tainted technologies**
- **Supply chain for the reactor pressure vessel is very constraint**
- **Decommissioning cost of about 1000 €/kW are neglected most of the time and further reduce profitability**
- **Comparing the LCOE of nuclear power plants to other renewable and fossil technologies, competitiveness is far from being in sight**
- **Until now no NPP was built under what is generally considered “economic” grounds, i.e. the decision of private investors in the context of a market-based, competitive economic system**
- **If Russia and China are able to provide the role of a global supplier needs to be seen, but both countries provide a strong government backed package including financing as a policy tool.**

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