THE WORLD NUCLEAR WASTE REPORT 2019

INTRODUCTION

BY ARNE JUNGJOHANN

Brussels, February 05, 2020

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FOCUS ON EUROPE AND CORE ISSUES

- Focus on Europe: Czech Republic, France, Germany, Hungary, Sweden, Switzerland, United Kingdom, Unites States.
- Selected countries represent a broad variety of characteristics (small vs. large, EU vs. non-EU, new-EU vs. old-EU etc.)
- Focus on nuclear waste from power production (not military/MIR)
- Focus on core issues:
  - How do countries classify nuclear waste?
  - How much nuclear waste has been generated and can be expected?
  - What risks does nuclear waste pose?
  - What concepts do governments pursue for nuclear waste management?
  - How much does managing the waste cost and how is financing secured?

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AIM & APPROACH

- Aim: assess the state of current affairs, to provide data as accurate as available, and to describe the approaches of utility, industry and state operators to address the challenges of nuclear waste.
- Aim: filling a research gap, allowing comparison across countries and (with periodical format) monitoring over time. Identifying sources of uncertainty, such as inconsistencies, contradictions and data gaps.
- Approach: descriptive, empirical, technical and analytical. No political recommendations.

OVERCOMING HURDLES

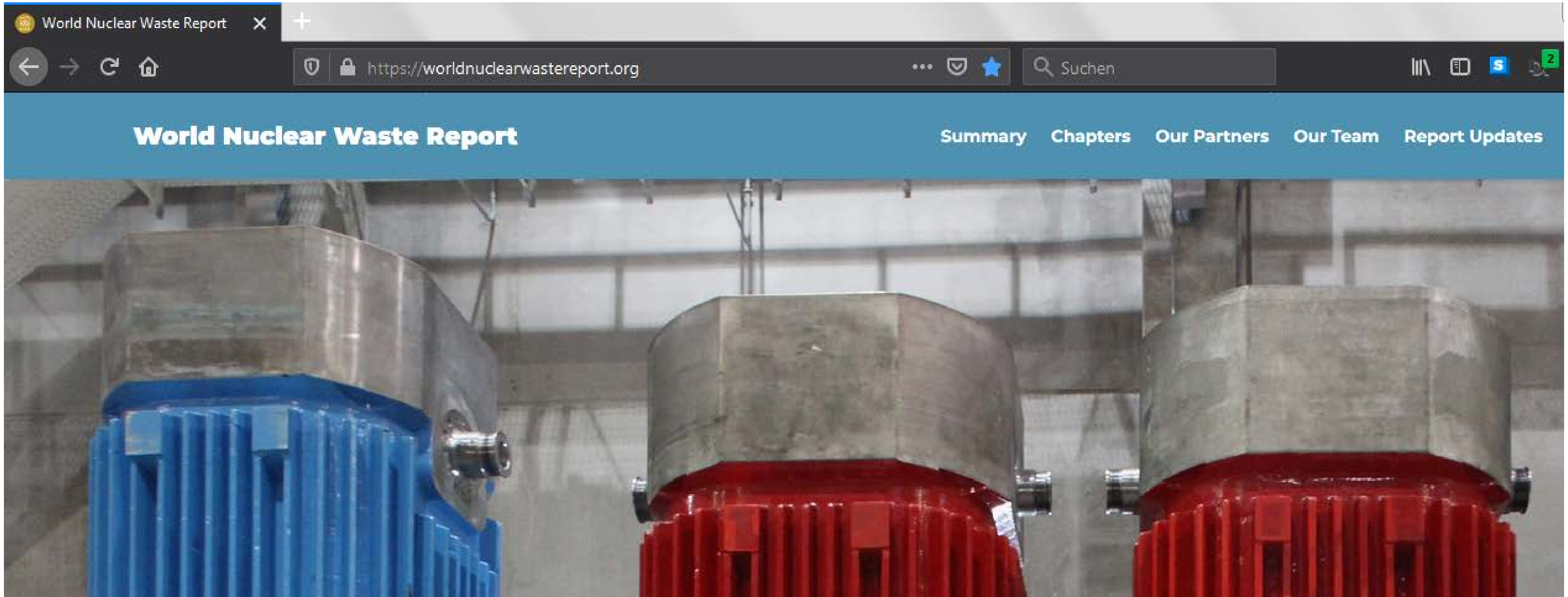
- Report faced hurdles such as large amount of data, varying practices of countries, language and terminology, inconsistencies in sources.
- Quality management elements include:
  - workshop in Brussels (February 2019),
  - author stylesheet (including terminology),
  - template for country chapters,
  - thorough review process with several feedback loops (including cross-chapter review and external proofreaders)
- no guarantee that the report is free of errors. We are grateful for corrections and suggested improvements (mail: info@wnwr.org)

THE ROAD AHEAD

Translations: Czech, French, German and Hungarian/Turkish.

Presentations: Berlin, Brussels, Washington DC, Budapest, Prague, Paris

www.WorldNuclearWasteReport.org



THE WORLD NUCLEAR WASTE REPORT 2019

QUANTITIES OF NUCLEAR WASTE

BY BEN WEALER

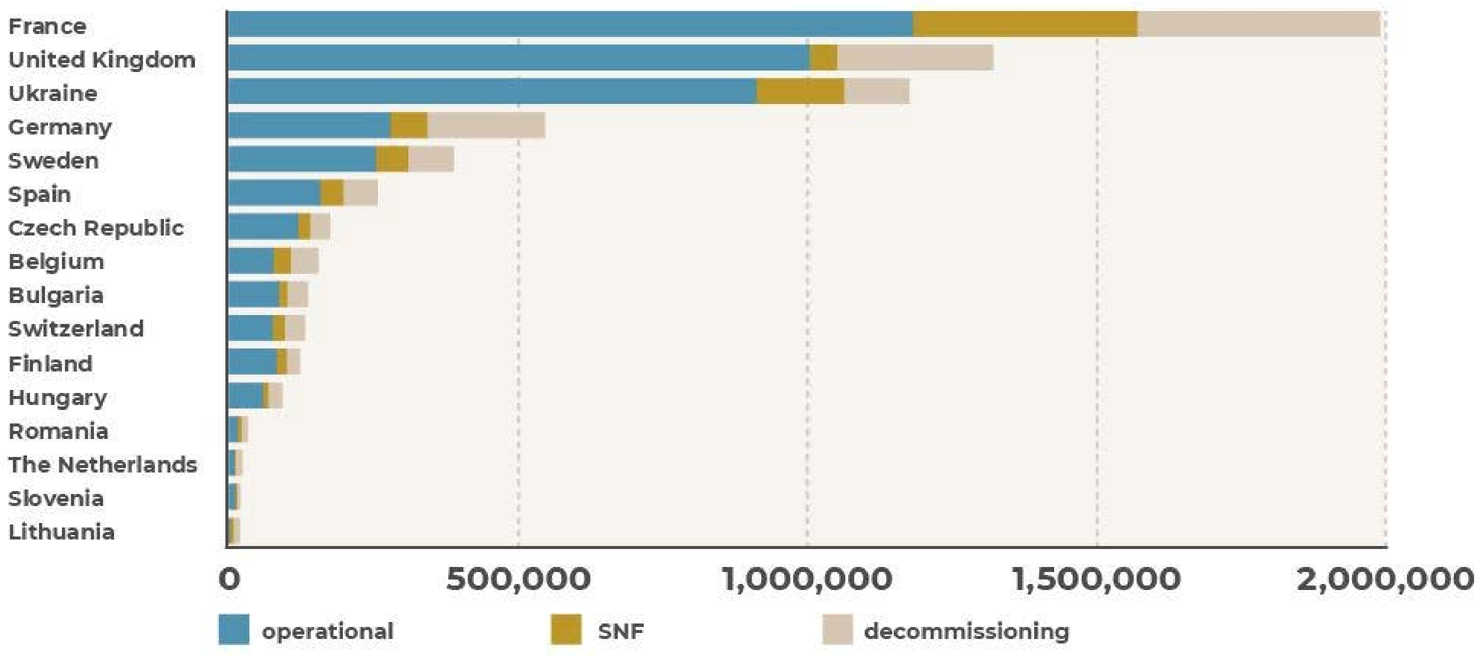
Brussels, February 05, 2020

WASTE QUANTITIES ALONG THE SUPPLY CHAIN

- **Uranium mining and fuel fabrication:** In order to use uranium as a fuel for electricity generation in nuclear reactors, uranium ore has to undergo several processing stages (i.e. mining, milling, conversion, enrichment, fuel fabrication). All these processes produce waste.
- **Operational waste:** The operation of nuclear power plants for electricity generation produces different kinds of nuclear waste in different kinds of physical states, of which the lion's share is low- and intermediate-level waste.
- **Spent nuclear fuel:** SNF is categorized as high-level radioactive waste. In Europe, reprocessing is still done in some countries (FR, NL, RUS), while most countries have suspended or stopped it for mainly economic reasons or never practiced it. The latest European country to show interest in reprocessing is Ukraine.
- **Decommissioning waste:** The process of defueling, deconstruction, and dismantling of a nuclear power plant is called decommissioning. The waste produced in the initial stages of decommissioning has the same characteristics as operational waste and can be characterized using the same approach, with one exception: it is generated in much larger quantities in a shorter period of time.

ESTIMATE: 6,6 MIO. M³ OF NUCLEAR WASTE IN EUROPE* UNTIL CLOSURE

FIGURE 2: Estimated nuclear waste from operation, spent nuclear fuel management, and decommissioning from European NPP fleet (operational and shut down) in m³ as of December 31, 2018



Source: Own compilation and estimation based on generation rate assumptions of IAEA 2007, US DOE 1997.

- **Operation:** 4,294,000 m³.
- **Spent nuclear fuel:** 874,000 m³.
- **Decommissioning:** 1,400,000 m³.
- **Quantities**: 6.6 million m³.
- Waste from mining and fuel fabrication **not included.**
- **Four countries account for over 75% of this waste**: France (30%), UK (20%), Ukraine (18%), Germany (8%).

*Excluding Russia and Slovakia.

BASIS FOR THE INVENTORIES: THE JOINT CONVENTION REPORTS

- For this section, the data for the different European national inventories is drawn from **the official documents published by the respective governments, regulatory agencies, or other responsible governmental bodies** under the Joint Convention.
- The 2001 **Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management** (hereafter Joint Convention) is the first legal instrument to address the issue of spent nuclear fuel and radioactive waste management.
- The agreement with the **International Atomic Energy Agency (IAEA)** includes the requirement to list the facilities for spent nuclear fuel (SNF) and radioactive waste management and to list the inventories of SNF and radioactive waste (Article 32).
- These national reports should be submitted for every review meeting, which has to take place no later than three years after the previous meeting (Article 30). The national reports from the sixth review meeting (in 2018) are the primary source for the waste quantities.

OPERATIONAL WASTE – LOW- AND INTERMEDIATE LEVEL WASTE (LILW)

- Varying **national inventory approaches make it difficult to compare the volume** of legacy waste in the countries, as operational waste is stored:
  - in **different physical states** (for instance liquid, solid, and pre-compressed),
  - or the waste has already been **preconditioned**, **conditioned, compacted**,
  - or **disposed** of.
  - Sometimes, the waste is clustered into **different categories**, such as LLW and ILW or LILW, or is still in other different forms.
- We exclude Russia and Slovakia as:
  - **Russia** gives only an estimate of low- and intermediate radioactive waste (of around 556 million m^3) with little information given on the origin (large amounts are from mining), waste classification, and state.
  - The most striking case is **Slovakia**, where information about nuclear waste forms such as “in pieces”, “drums” or “pallets” does not allow any classification of volumes.

TABLE 2: Low- and intermediate level waste in Europe in interim storage and disposed (rounded figures) as of December 31, 2016

Country	LILW in interim storage (m^3)	LILW disposed (m^3)	Total generated LILW (m^3)
BELGIUM	23,200	No disposal facility operational.	**23,200**
BULGARIA	11,900	No disposal facility operational.	**11,900**
CZECH REPUBLIC	1,750	11,500	**13,250**
FINLAND	1,970	7,600	**9,600**
FRANCE	180,000	853,000	**1,033,000**
GERMANY	45,200	84,100	**129,300**
HUNGARY	10,600	876	**11,500**
LITHUANIA	44,000	No disposal facility operational.	**44,000**
THE NETHERLANDS	11,100	No disposal facility operational.	**11,100**
ROMANIA	1,000	No disposal facility operational.	**1,000**
SLOVENIA	3,400	No disposal facility operational.	**3,400**
SPAIN	6,700	32,200	**38,900**
SWEDEN	13,800	39,000	**52,800**
SWITZERLAND	8,400	No disposal facility operational.	**8,400**
UKRAINE *	59,400	No disposal facility operational.	**59,400**
UNITED KINGDOM	130,000	942,000	**1,072,000**
TOTAL	**552,400**	**1,970,000**	**2,522,000**

Source: Own depiction based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management and ONDRAF/NIRAS 2017.
Note: *Excluding (stored and disposed) waste in the Chernobyl zone.

*Excluding Russia and Slovakia.

LILW INVENTORY IN EUROPE*

- More than **550,000 m^3 are currently in interim storage**.
- Only half of the observed countries have disposal facilities for LILW (mostly LLW).
- Close to **2,000,000 m^3 disposed** (1.8 million m^3 by UK and France).
- **However, this does not mean that the waste is successfully eliminated for the coming centuries.** Asse II in DE: 220,000 m^3 of mixed disposed waste and salt need to be retrieved.
- Therefore, **the term final disposal should be used with caution.**

TABLE 3: Reported spent nuclear fuel inventories in Europe and amount in wet storage as of December 31, 2016

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: Own depiction, based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

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).

SPENT NUCLEAR FUEL INVENTORIES

Spent nuclear fuel (SNF) is categorized as **high-level radioactive waste**.

So far, worldwide **no disposal facility** operational.

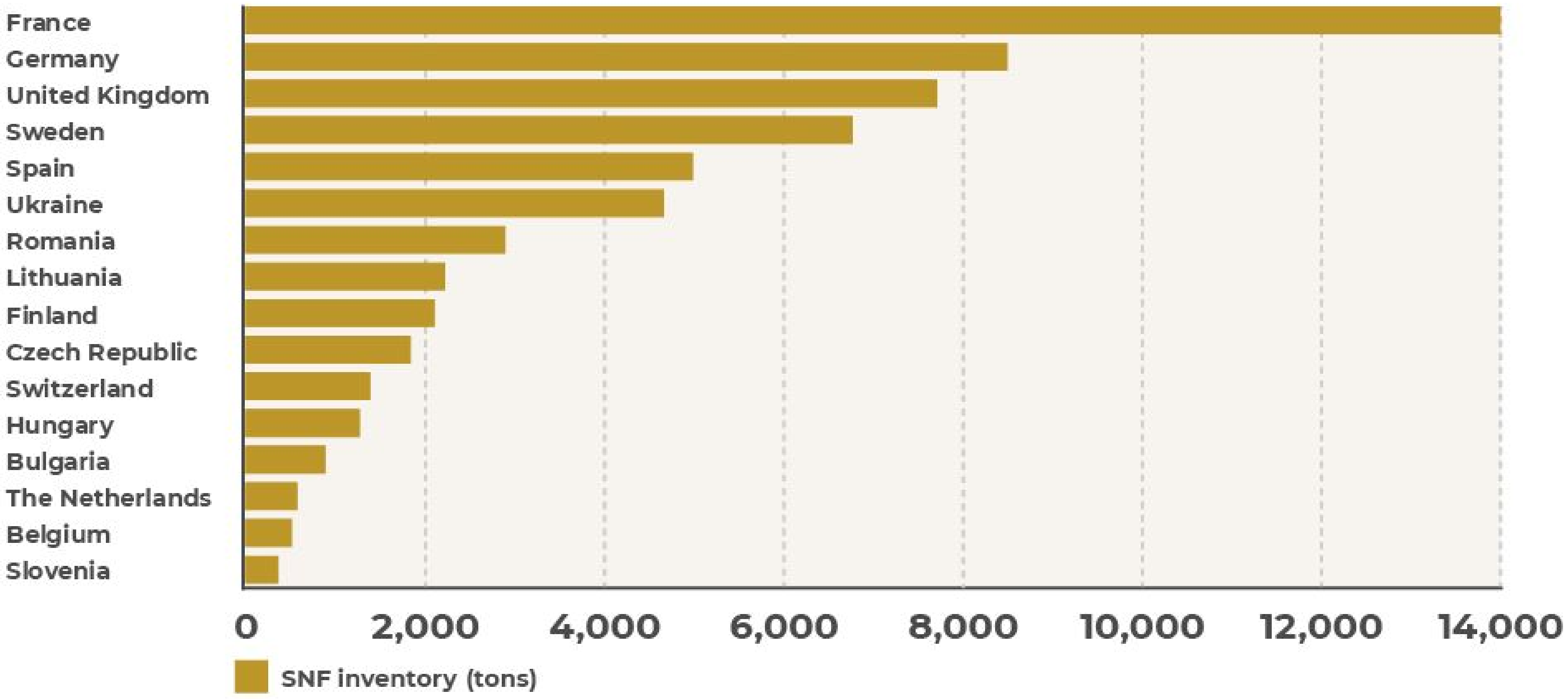
In Europe (excluding Russia and Slovakia) more than ca **60,500 tons** of SNF are stored.

The majority in **France** (25%), **Germany** (15%) and **U.K.** (14%).

SNF is generally stored in reactor cooling pools or interim storage facilities (dry or wet). Around 49,000 tons or 81% of the SNF is **wet storage**.

SPENT NUCLEAR FUEL IN INTERIM STORAGE IN EUROPE

FIGURE 3: Spent nuclear fuel in interim storage in Europe (excluding Russia, and Slovakia) in tons as of December 31, 2016



Source: Own depiction based on reports published under Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

TABLE 1: Decommissioned reactors worldwide as of May 31, 2018

Country	Reactor	Capacity in MW	Decommissioning End in	Operational Years
GERMANY	5	1,017 (total)		
	Niederaichbach	100	1995	1
	HDR Großwelzheim	25	1998	2
	VAK Kahl	15	2010	24
	Würgassen	640	2014	23
	Gundremmingen-A	237	2016	11
JAPAN	1	12 (total)		
	JPDR	12	2002	13
UNITED STATES OF AMERICA	13	4,922 (total)		
	Elk River	22	1974	5
	Shippingport	60	1989	25
	Pathfinder	59	1993	1
	Shoreham	809	1995	0
	Fort St. Vrain	330	1997	13
	Maine Yankee	860	2005	24
	Saxton	3	2005	5
	Trojan	1,095	2005	17
	Yankee NPS	167	2006	31
	Big Rock Point	67	2006	35
	Haddam Neck	560	2007	29
	Rancho Seco-1	873	2009	15
	CVTR	17	2009	4
TOTAL		5,951		

Source: Own depiction based on Schneider et al. (2018).

DECOM-MISSIONING

Large quantities of LILW will arise after the reactors are shut down and subsequently decommissioned.

As of 2018, only **19 nuclear power plants have been decommissioned worldwide**, of which only five were in Europe.

Worldwide **not one large-scale reactor** with 1 GW of capacity and 40 years of operation has been **decommissioned**.

Although decommissioning works are ongoing in Europe, **reports of quantities of decommissioning waste are hard to find**.

EUROPE'S PILES OF NUCLEAR WASTE: SUMMARY

- European countries have produced **several million cubic meters** of nuclear waste (not even including uranium mining and processing wastes).
- **No adequate disposal solutions:** only half of the observed countries have disposal facilities for LILW and not one (worldwide) for HLW.
- **Long-term:** Europe's nuclear fleet is estimated to generate over it's lifetime around **6.6 million m^3** of nuclear waste. If stacked in one place, this would fill up a football field 919 meters high: three times higher than the Eiffel Tower or 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai.
- **All this waste needs disposal.**
- The ongoing generation of nuclear waste and the upcoming decommissioning of nuclear facilities poses **an increasing challenge**, because storage facilities in Europe are slowly running out of capacity.

THE WORLD NUCLEAR WASTE REPORT 2019

COSTS AND FINANCING

BY BEN WEALER

Brussels, February 05, 2020

BASIC LIABILITY FOR DECOMMISSIONING AND WASTE MANAGEMENT

- **In general:**
  - In order “to avoid imposing undue burdens on future generations” (Article 3 of the IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management Convention), **one unifying concept, observed in nearly every country, is the polluter-pays-principle, which makes the operator liable for the costs of these activities.**
  - These obligations and liabilities arise with the start of operation.
- **But:**
  - sooner or later states often become directly involved at some point, including financially.
  - This is especially true for waste management, as the polluter-pays-principle applies in most cases only for the decommissioning and dismantling of the reactors.
  - For the long-term storage of radioactive waste, a variety of organizational models has evolved in which the national authorities – not the operator of the nuclear facility – more or less assume technical and financial liability for the very long-term issues of waste management.

OVERVIEW AND NATURE OF THE FUNDS

- **External segregated fund:** The operators pay their financial obligation into an external fund. Here, private or state-owned independent bodies manage the funds. An external fund can exist with or without transfer of the liabilities and with or without a short-fall guarantee by the operator.
- **Internal non-segregated fund:** The operator pays into a self-administrated fund and manages the financial resources, which are held within its own assets
- **Internal segregated fund:** The operator is obliged to form and manage funds autonomously. The assets must be segregated from other businesses or earmarked for decommissioning and waste management purposes.
- **Public budget:** State authorities take over the financial responsibility including the accumulation of financial resources (for instance via taxes and levies). This option is typically used for legacy nuclear power plant fleets and orphan sites (sites where the former operator has declared bankruptcy or simply does not exist anymore, such as the former East German reactors).

ACCUMULATION OF THE FUND

- The accumulation of the funds can either be achieved by y a fee, a levy set on the sale of electricity, “internally” by the operators who set aside funds from the revenue obtained from the sale of electricity, or by the investment of the funds.
- **A crucial aspect is whether funds or future provisions are based on discounted or undiscounted costs:**
  - If the costs are not discounted, the operators have to set aside the full amount of the estimated costs. Only a few nuclear funding systems use undiscounted costs.
  - If costs are discounted, the funds are expected to grow over time. Here the provisions are determined using the inflation rate until the due date and then discounted with an interest rate, which is supposed to represent the expected rate of return.
  - The employed discount rates range widely (e.g. 5.5% in Germany, 1.5% in Spain).
  - A cost escalation rate is not always assumed.
- **Example:** In Germany, the set aside funds of €24.1 billion for all waste management related activities are expected to grow nearly fourfold to €86 billion by 2099.

COST EXPERIENCES AND ESTIMATIONS

- In order to accumulate funds, costs need to be estimated. This is a critical aspect of funding, especially for unknown projects like a deep geological facility for high-level waste.
- Different cost estimation methods are conceivable (e.g. order-of-magnitude estimate, budgetary estimate, definitive estimate).
- In reality, most cost estimates are budgetary estimates based on studies and estimates from the 1970s and 1980s, which are then extrapolated.
- In most cases, the waste management organization is responsible for developing cost estimates for the long-term management of radioactive waste. This organization can be state-owned (such as in the UK, Germany and Spain) or in some cases utility-owned, as in Sweden and Switzerland.
- In most cases cost estimates are not publically available (e.g. in Germany, the cost of both decommissioning and long-term waste management is based on expert opinions, produced by the private companies for the utilities and not public).

COSTS AND FINANCING SUMMARY

- Governments do not apply the polluter-pays-principle consistently, and very large costs fall on taxpayers.
- In most cases cost estimates are drawn up the operators, industry, or state agencies and not public) and not publically available for independent energy experts.
- Governments fail to properly estimate the costs for decommissioning, storage, and disposal of nuclear waste. All cost estimates have underlying uncertainties due to long time-scales, cost increases, and estimated discounting (fund accumulation) rates. Estimates are systematically biased in an optimistic direction
- Therefore, no country has both estimated costs precisely and closed the gap between secured funds and cost estimates. In most cases, only a fraction of the funds needed has been set aside.
- As an increasing number of reactors are shutting down ahead of schedule due to unfavorable economic conditions, the risk of insufficient funds is increasing. These early shutdowns, shortfalls in funds, and rising costs are forcing some plants to delay decommissioning in order to build up additional funds. Countries are also considering ways to enable facilities to recover their costs through higher fees, subsidized prices, and longer operation times, for instance in the US and Japan.

ANNEX

REPROCESSING

TABLE 4: High-level and intermediate-level waste from reprocessing in storage as of December 31, 2016

Country	Active Reprocessing	HLW [m³]	ILW [m³]
BELGIUM	No	285	3,132
BULGARIA	No	n.a.	n.a.
FRANCE	Yes	3,740	42,800
GERMANY	No	577	n.a.
HUNGARY	No	102	n.a.
THE NETHERLANDS	Yes*	91	n.a.
RUSSIA	Yes	n.a.	n.a.
SPAIN	No	n.a.**	n.a.
SWITZERLAND	No	114**	n.a.
UNITED KINGDOM	No	1,960	n.a.

Source: Own depiction based on reports under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.
Notes: *in France. ** additional waste stored in France.

- Most countries had to send their SNF abroad for reprocessing to either France, the UK, or Russia (only a few central European countries continue to do so).
- Vitrified waste (mostly HLW) is sent back to the country of origin.
- In 2018, France has the last commercial reprocessing plant in Western Europe.
- More than half of the HLW comes from France. The only two countries specifying the amounts of ILW are France and Belgium.

FUNDING SYSTEMS FOR DECOMMISSIONING

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

FUNDING SYSTEMS FOR DISPOSAL

TABLE 7: Funding systems for disposal in France, Germany, and the US as of December 2018

	FRANCE*	GERMANY	US
FINANCING SCHEME	internal segregated and restricted fund, then moved to waste management agency (ANDRA) at construction start	external segregated fund	external
ACCUMULATED BY	levy on electricity price	investment of the funds	previously levy on electricity price but no longer collected
TOTAL COST ESTIMATES	US$ 34.9 billion	US$ 19.8 billion**	US$ 96 billion
SET ASIDE FUNDS, (IN % OF COST ESTIMATE)	US$ 11 billion (32%)	US$ 27.2 billion (>100%)**	US$ 34.3 billion (36%)

Source: Own depiction
Notes: *only applies to EDF ** including interim storage, LILW and HLW disposal.

THE WORLD NUCLEAR WASTE REPORT 2019

INTRODUCTION AND OVERVIEW

GORDON MACKERRON

Brussels, February 05, 2020

APPROACH

- We wanted to provide a systematic review of nuclear waste management practices globally, but with an initial focus primarily on Europe
- It became clear early on that - such was the diversity of practices across countries - that comparative evaluation was difficult
- We concentrated on wastes arising from the operation of nuclear power plants because these posed the greatest management problems and high levels of radioactivity
- Despite the widespread (but not universal) acceptance that deep geological disposal is the best, or least-worst, management strategy for the most hazardous wastes, no country yet has an operational facility

CLASSIFICATION

- Despite international efforts to establish common practices, there are many inconsistencies and variations in practice
- There is no agreement on what counts as nuclear waste: plutonium is sometimes a ‘resource (France) and sometimes – at least recently – a liability/waste (UK)
- High level wastes (spent fuel and residual products of plutonium separation) are always regarded as wastes, and pose high hazards
- Most countries adopt variable definitions of low (LLW) , intermediate (ILW) and high level waste (HLW)
- Lower levels of waste have high volumes and relatively low radioactivity: HLW has small volumes but very high and long-lasting radioactivity

WASTE SOURCES

- Nuclear wastes arise along the whole fuel supply as follows:
- From uranium mining and fuel fabrication
- From operation of nuclear plants
- From spent nuclear fuel (and reprocessing that fuel)
- From decommissioning of reactors and other contaminated plant

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WASTE MANAGEMENT CONCEPTS

- Much lower activity wastes are currently disposed, usually by engineered shallow facilities
- But despite official acceptance of deep geological disposal as the favoured strategy for higher activity wastes, only Finland has started to construct one, and this is subject to significant technical dispute
- After nearly 70 years of nuclear power generation, this means that ever larger quantities of higher activity wastes are stored, and some will continue to be stores for over 100 years.
- Risks from storage practice, where facilities are often designed for the short term, are therefore rising

RISKS AND HEALTH

- Nuclear waste is a health hazard due to routine gaseous and liquid emissions and from reprocessing spent fuel
- Reprocessing is especially problematic due to proliferation risks, high potential human exposures and environmental contamination
- There is a lack of comprehensive information, qualitative and quantitative, of nuclear waste risks

COSTS AND FINANCING

- This is an area of very diverse of often poor practice
- Governments do not apply the polluter-pays-principle consistently, and very large costs fall on taxpayers
- Governments also fail to estimate properly the costs of waste management and estimates are systematically biased in an optimistic direction
- There are therefore very large funding gaps and limited secured funds available

EUROPEAN COMMISSION REPORT OF 17 DECEMBER 2019

- This reports on progress of implementation of Council Directive 2011/70/EURATOM on radioactive waste and spent fuel
- Report found significant shortcomings in practices of several Member States (MS) e.g. one third did not have adequate provisions for the independence, legal powers and resources of competent national authorities, and one third did not have defined key performance indicators
- Several MS do not have concrete disposal plans
- Estimated total costs now EUR 422-566 billion, up from 400 bn. in last report
- Infringement procedures launched in 2018 for non-compliance with legal requirements in 5 MS.