THE WORLD NUCLEAR WASTE REPORT 2019

EXECUTIVE SUMMARY

Focus Europe.

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EXECUTIVE SUMMARY

The **WORLD NUCLEAR WASTE REPORT (WNWR)** shows that governments around the world have been struggling for decades to develop and implement comprehensive nuclear waste management strategies. Much of the task will fall onto future generations.

WASTE MANAGEMENT CONCEPTS

More than 70 years after the start of the nuclear age, no country in the world has a deep geological repository for spent nuclear fuel in operation. Finland is the only country that is currently constructing a permanent repository for this most dangerous type of nuclear waste. Besides Finland, only Sweden and France have de facto determined the location for a high-level waste repository in an early confinement process. The US is operating the Waste Isolation Pilot Project (WIPP). However, this repository is only used for long-lived transuranic waste from nuclear weapons, not for spent nuclear fuel from commercial reactors.

Despite multiple examples of failed selection procedures and abandoned repositories, current national and international governance show a preference for geological disposal. This requires clear and ambitious conditions for the site selection, exploration, and approval processes. Still, there is no guarantee for the feasibility of deep geological disposal. This is why the process of searching for such repositories must be implemented with extraordinary care on the basis of industrial feasibility and accompanied by appropriate monitoring. Some scientists consider that monitored, long-term storage in a protected environment is more responsible, much faster to achieve and should therefore be implemented. Overall there is a strong consensus that the current state of research and scientific debate and exchange with politicians and involved citizens is not adequate for the magnitude of the challenge.

The conditioning, transport, storage and disposal of nuclear waste constitute significant and growing challenges for all nuclear countries. These developments show that **governments and authorities are under pressure to improve the management of interim storage and disposal programs.** Accordingly, standards must be implemented for the governance of the programs, including planning quality and safety, quality assurance, citizen participation and safety culture.

Interim storage of spent nuclear fuel and high-level waste will continue for a century or more. With deep geological repositories not available for decades to come, the **risks are increasingly shifting to interim storage.** The current storage practices for spent nuclear fuel and other easily dispersible intermediate- and high-level waste forms were not planned for the long-term. These practices thus represent a growing and particularly high risk, especially when other options are available (solidification, dry storage) in hardened facilities. Extended storage of nuclear waste increases risks today, adds billions in costs, and shifts these burdens to future generations.

QUANTITIES OF NUCLEAR WASTE

European countries have produced several million cubic meters of nuclear waste (not even including uranium mining and processing wastes). By the end of 2016, **France, the United Kingdom and Germany were Europe's biggest producers of nuclear waste** along the nuclear fuel chain.

Over 60,000 tons of spent nuclear fuel are stored across Europe (excluding Russia and Slovakia), most of which in France (*Table 1*). Within the EU, France accounts for 25 percent of the current spent nuclear fuel, followed by Germany (15 percent) and the United Kingdom (14 percent). Spent nuclear fuel is considered high-level waste. Though present in comparably small volumes, it makes up the vast bulk of radioactivity.

TABLE 1: 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).

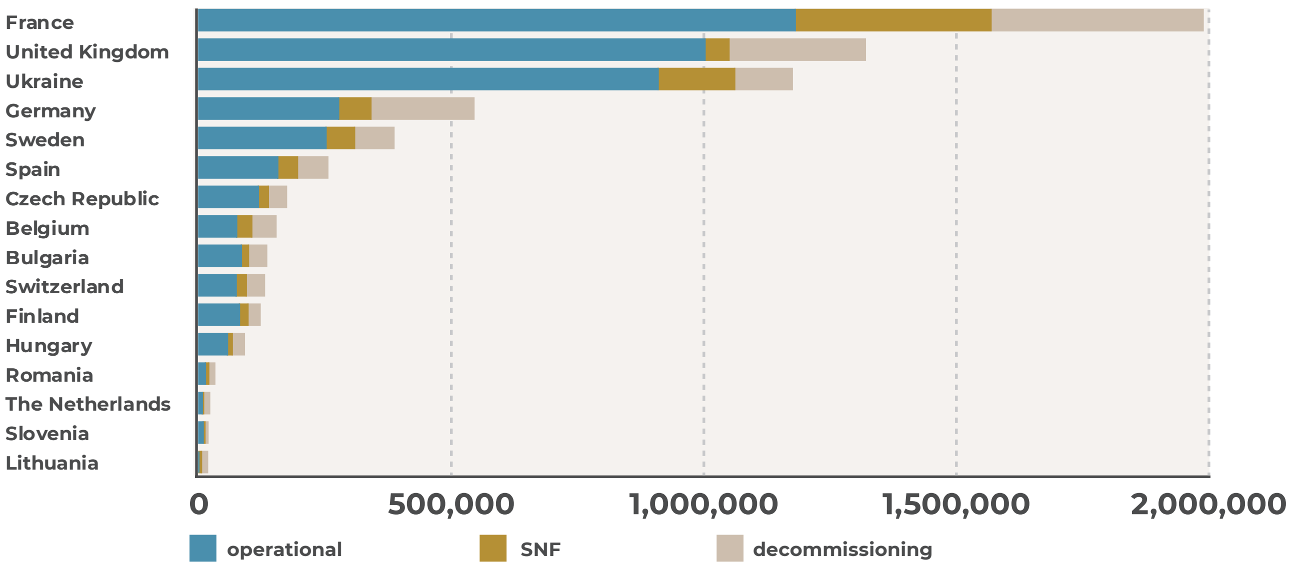
In the UK, for instance, high-level waste amounted to less than 3 percent of nuclear waste's volume, but almost 97 percent of the inventory's radioactivity. Most of spent fuel has been moved into cooling pools (so-called wet storage) to reduce heat and radioactivity. As of 2016, 81 percent of Europe's spent nuclear fuel was in wet storage. It would be safer to transfer the spent nuclear fuel into dry storage in separate facilities. A large share of the stored spent nuclear fuel in France and the Netherlands is planned to be reprocessed. Most other European nuclear countries (Belgium, Bulgaria, Germany, Hungary, Sweden, Switzerland, and most recently the UK) have indefinitely suspended or terminated reprocessing. Not all countries report about the quantities of spent fuel that have been reprocessed. In most cases only vitrified high-level waste from reprocessing is reported. The same accounts for the vast amounts of reprocessed uranium, plutonium, intermediate-level waste, and spent mixed oxide fuel (MOX) that requires an extensive additional intermediate storage period.

Around 2.5 million m³ of low- and intermediate-level waste has been generated in Europe (excluding Slovakia and Russia). Around 20 percent of this waste (0.5 million m³) has been stored across Europe, waiting for final disposal. This amount is constantly increasing with no full disposal route anywhere. Around 80 percent of this waste (close to 2 million m³) has been disposed of. However, this does not mean that the waste is successfully eliminated for the coming centuries. For instance, the Asse II disposal site in a former salt mine in Germany suffers from continuous inflow of groundwater. The 220,000 m³ of mixed disposed waste and salt need to be retrieved, which is a complex and costly task. The quantities are now five times the original amount of waste due to the mixture of salt and radioactive waste. Therefore, the term final disposal should be used with caution.

The decommissioning of nuclear facilities will create additional very large amounts of nuclear waste. Exlcuding fuel chain facilities, **Europe's power reactor fleet alone may generate at least another 1.4 million m³ of of low- and intermediate level waste from decommissioning.** This is a conservative estimate as decommissioning experiences are scarce. As of 2018, 142 nuclear power plants were in operation in Europe (excluding Russia and Slovakia).

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, especially for spent nuclear fuel.** For example, storage capacity for spent fuel in Finland has reached already 93 percent saturation. Sweden's decentralized storage facility CLAB is at 80 percent saturation. However, not all countries report on saturation levels of storage capacities, making a complete overview impossible.

FIGURE 1: 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.

Over its lifetime, **the European nuclear reactor fleet is estimated to produce around 6.6 million m^3 of nuclear waste** (*Figure 1*, excluding Russia and Slovakia). If stacked in one place, this would fill up a football field 919 meters high, 90 meters higher than the tallest building in the world, the Burj Khalifa in Dubai. The calculation includes waste from operation, spent nuclear fuel, and reactor decommissioning. This estimate and the ones above are based on conservative assumptions. The actual quantities of nuclear waste in Europe are likely higher. **With a share of 30 percent, France would be Europe's greatest producer of nuclear waste, followed by the UK (20 percent), the Ukraine (18 percent), and Germany (8 percent).** These four countries account for more than 75 percent of the European nuclear waste.

Apart from Russia, which is still an active producer of uranium, **Germany and France have the largest inventory of nuclear waste from uranium mining in Europe.** Officially, the former French uranium mining industry generated 50 million tons of mining residues, but independent experts estimate that it is much higher. The former German Democratic Republic (GDR) mined much larger quantities of uranium ore than France. The mining legacies comprise some 32 km^2 of facility areas, 48 heaps with a volume of low active rocks of 311 million m^3 and four tailing ponds holding a total of 160 million m^3 of radioactive sludge. Today, the EU imports most uranium, creating large amounts of nuclear waste outside of Europe.

COSTS AND FINANCES

Nearly every government claims to apply the polluter-pays-principle, which makes operators liable for the costs of managing, storing, and disposing of nuclear waste. In reality, however, **governments fail to apply the polluter-pays-principle consistently.** Most countries enforce it only on decommissioning, although there are some cases where the government takes over the liability for decommissioning (for example, for the reactors in former East Germany). Bulgaria, Lithuania, and the Slovak Republic receive EU support for decommissioning in exchange for having closed their older Soviet-era nuclear power plants. Most countries do not enforce the polluter-pays-principle for the disposal costs of nuclear waste. For this, national authorities more or less end up assuming liability as well as the responsibilities for long-term waste management and disposal. The operator is, however, required to contribute to financing the long-term costs. Even in countries in which the polluter-pays-principle is a legal requirement, it is applied incompletely. For instance, a nuclear power plant operator will not be held financially liable for any problems arising once a final disposal facility is closed; this is the case for the German Asse II disposal facility, where the retrieval of large amounts of waste has to be paid for by taxpayers.

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. A major reason for the uncertainty is the lack of experience in decommissioning and waste disposal projects in particular. Only three countries, the US, Germany and Japan, have completed decommissioning projects including full dismantling and thus generated data. As of mid-2019, of 181 closed power reactors in the world, only 19 had been fully decommissioned, of which only 10 to "green field". But even these limited experiences show a wide range of uncertainty, up to a factor of five. In the US, decommissioning costs varied between reactors from US$280/kW to US$1,500/kW. In Germany, one reactor was decommissioned for US$1,900/kW, another one for US$10,500/kW.

Many governments base their cost estimates on outdated data. Many countries reviewed here such as France, Germany, and the US base their estimates on studies from the 1970s and 1980s, rather than on the few existing real-data cases. Using outdated data, in most cases drawn up by operators, industry, or state agencies, likely leads to low-cost estimates and overly optimistic conclusions.

Many governments apply overly optimistic discount rates. One key factor leading to the underestimation of the costs for decommissioning and nuclear waste management is the systematic use of overly optimistic discount rates. A fundamental aspect of funding decommissioning and waste management is the expectation that the funds will grow over time. In Germany, for instance, the funds of €24.1 billion (US$ 27.2 billion) set aside for all waste management-related activities are expected to grow nearly fourfold to €86 billion by 2099. The discount rates employed range widely, and not all countries calculate cost increases, although it is likely that costs will increase faster than the general inflation rates (*Table 2*).

TABLE 2: 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.

In order to guarantee the availability of sufficient funding for decommissioning, waste management and disposal, the financing schemes need to create secure holding conditions for the funds ("ring-fencing"). They also need to make sure that the resources set aside are sufficient to cover the real costs. Some countries fulfill one condition but fail on the other.

Countries differ significantly on how they plan the financing of nuclear waste management, storage, and disposal. Not all nuclear countries require decommissioning funds to be managed externally and segregated from the operator or licensee. Decommissioning is in some cases still financed through internal segregated and restricted funds, although the money for long-term waste management is managed externally in most countries. Financing decommissioning and storage is complex; in most cases, multiple funding systems are in place in one country.

In light of different national approaches, governments do not always define what "decommissioning" includes. Nuclear waste management is an important aspect of decommissioning, as is spent fuel management. But both are not always defined under "decommissioning", making it hard to compare costs across different countries. **The processes of decommissioning, storage, and disposal are heavily interlinked. That is why an integrated external segregated and restricted fund seems to be the most suitable approach to finance the future costs for these processes.** Only a few countries have opted for this solution, notably Sweden, the UK, and Switzerland; although, Switzerland has two funds, one for decommissioning and one for waste management. **No country has secured the complete financing of decommissioning, storage, and disposal of its nuclear waste.** Doing so will be a challenge for all countries using nuclear power.

TABLE 3: Integrated funding systems for decommissioning and waste management in Sweden, Switzerland, and the UK as of December 2018

	SWEDEN	SWITZERLAND	UK*
FINANCING SCHEME	one external segregated and restricted fund	two external segregated funds (for waste management and for decommissioning)	one external segregated and restricted fund
ACCUMULATION	fee on electricity price (set individually for each plant)	payment by operator	payment by operator
TOTAL COST ESTIMATES	US$ 10.7-11.8 billion	US$ 24.6 billion***	US$ 26.5 billion**
SET ASIDE FUNDS, (IN % OF COST ESTIMATE)	US$ 7.2 billion**** (61-67%)	US$ 7.39 billion (30%)	US$ 12.1 billion (46%)

Source: Own depiction.
Notes: *EDF Energy reactors **as of 2018 ***Estimated total costs for a 50-year operating period as of 2019 ****as of 2017

Today, 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. For instance, Sweden has set aside funds for decommissioning and waste management of two thirds of the estimated costs so far, the United Kingdom less than half for its operational reactors, and Switzerland not even a third (*Table 3*). The same can be observed of funding waste disposal. France and the US have set aside funds for disposal that would cover only around a third of the estimated costs. As an increasing number of reactors are closing ahead of schedule due to unfavorable economic conditions, the risk of insufficient funds is increasing. These early closures, shortfalls in funds, and rising costs are pushing some nuclear power plant operators to delay other closures and 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 lifetime extensions, for instance in the US and Japan.

ORIGINS AND CLASSIFICATIONS

Countries differ significantly in how they define nuclear waste. They differ in whether spent nuclear fuel and some of its separated products (plutonium and reprocessed uranium) are considered waste or a resource. For instance, spent fuel and the plutonium it contains qualify as waste in most countries because of the hazardous nature and the high costs of plutonium separation and use. However, France defines plutonium as a potential resource and requires reprocessing by law. Reprocessing both postpones the waste issue and makes it more complex and expensive.

Countries differ significantly in how they categorize nuclear waste. No two countries have identical systems. Germany differentiates only between heat-generating and other waste. The UK uses the level of radioactivity to classify its waste. France and the Czech Republic consider both, the level of radioactivity and the time period of radioactive decay (half-life). The US system differs fundamentally from that of European countries in that it bases classification on the origins of waste, not its characteristics.

Countries differ significantly in how they report about generated amounts of nuclear waste. All countries publish regularly information on the amount of waste they produce and associated management schemes. Yet not all countries report in a thorough way. In some cases, the reported information cannot be used to estimate volumes (such as Slovakia). Some country reports (such as the Dutch and the Belgian) lack an up-to-date inventory of spent nuclear fuel. Russia gives little information on the classification and state of its nuclear waste inventory.

These differences and inconsistencies of how countries define, categorize and report about nuclear waste makes gathering data and comparing countries very complex. The different national approaches reflect a lack of coherency in how countries manage nuclear waste. They occur in the face of international attempts to establish common safety principles and creating a peer review process of country practices. The International Atomic Energy Agency (IAEA) provides a broad framework of classification for nuclear waste. The 2001 Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management constitutes a default position for many countries, however, but with largely differing implementation practices. With the 2011 Euratom Directive, the EU attempted to harmonize waste classification systems for its member states, but with limited success.

RISKS FOR THE ENVIRONMENT AND HUMAN HEALTH

Nuclear waste constitutes a health hazard for several reasons. First are the reported health impacts from routine gaseous and liquid waste emissions from nuclear facilities. Second are the very large global collective doses from reprocessing. And third is the unsatisfactory and unstable condition of much of the nuclear waste already created. High-level waste (HLW) in the form of spent nuclear fuel and vitrified waste from reprocessing contains more than 90 percent of the radioactivity in nuclear waste. However, there is no fully operational HLW final disposal site in the world. The continued practise of storing spent nuclear fuel for long periods in pools at nuclear power plants (wet storage) constitutes a major risk to the public and to the environment. **Reprocessing of spent nuclear fuel in particular creates more accessible and dispersible forms of highly dangerous radioactive wastes, and poses increased challenges,** including proliferation risks, high exposures to workers and the public, and radioactive contamination of the environment.

Information is limited to properly assess risks from nuclear waste and develop hazard rankings. Only a few countries publish information, for example, on nuclide inventories in wastes. National governments or state agencies are primarily responsible for collecting and disseminating such data. This data is needed to properly assess the potential causal relationship between exposures and health effects. So far, no comprehensive hazard scheme exists for the radionuclides in nuclear waste.

There is a lack of comprehensive, high quality studies to assess risks from nuclear waste. Risks may be derived from epidemiological studies, but the few specific ones that exist are of limited quality. Some studies suggest increased cancer rates, for example, but are individually too small to give statistically significant results. Meta-analyses could combine smaller studies to generate larger datasets, which could produce statistically significant findings. However, meta-analyses on the health impacts of nuclear waste are notable for their virtual absence. In addition, in order to assess risks, it is also necessary to measure doses accurately. Overall, the analysis reveals an astonishing lack of quantitative and qualitative information on risks associated with nuclear waste.

COORDINATOR NOTE ON METHODOLOGY AND OUTLOOK

The **World Nuclear Waste Report (WNWR)** provides an international comparison how countries manage nuclear waste, outlining their current status and historical trends. With its focus on Europe, it begins filling a significant research gap. Outside of Europe, there is even more variation of practices by operators and governments in dealing with the challenge of nuclear waste. Social, political, technical, and financial challenges on the way to finding a sound long-term solution for these particular problem wastes are high.
As this is the first of its kind, the report faced many hurdles in its aim to provide a meaningful overview based on a large amount of complete factual and numerical data. Not only do countries differ significantly how they define nuclear waste, how they classify its different types, and how they report about its generated amounts. The research also revealed a lack of data, faced language barriers, varying uses of terminology in countries, and inconsistencies in sources. All of this makes the assessment highly complex.

To overcome these hurdles and to avoid errors, the project team developed a specific quality management approach for contributors, editors, and proofreaders. Elements included a workshop in Brussels (February 2019), developing an author stylesheet (including terminology), developing a template for country chapters, and implementing a thorough review process with several feedback loops. Each chapter has been drafted by a single author with a specific expertise on the topic; some authors have drafted more than one chapter. However, the chapters are not attributed to individual authors to ensure a high-quality editorial process. Each chapter draft went through a four-stage review process:

- an initial editing by the lead editor and two more persons from the project team;
- a cross-chapter review by the lead editor;
- an overall review of the full text by the lead editor, by three other members of the project team, and by two external proofreaders;
- and a final review to develop the executive summary.

Producing the report has been a tremendous task of more than a dozen experts in this field over the course of one and a half years. It allowed for the text to improve significantly over time. The authors, editors, and proofreaders have done their utmost to verify and double-check. However, this intense process does not guarantee that the report is free of errors. In case there are, we are grateful for corrections and suggested *improvements*.

This first edition of the **WNWR** aims at laying the groundwork for future research on the topic. New questions have come up, and some should be addressed in the next edition of the report, such as the risks that the extended use of unsuitable interim storage poses and the foreseeable lack of capacities for interim storage, proliferation, the threat of terrorism and other security issues when assessing the risk of nuclear power, the practice of uranium mining, the clearance of fractions of the waste by free measurement, and the role of public participation in site selection processes. The next edition could also expand its geographical scope to other nuclear countries. Among them are Canada, China, Finland, Japan, Russia, South Korea, Spain, and Ukraine.