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The World Nuclear Waste Report (WNWR)

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Authors: Ian Fairlie, Gordon MacKerron, Ben Wealer.

Editors: Arne Jungjohann, Anna Turmann.

About the authors:

Dr Ian Fairlie is an independent consultant on radiation in the environment with degrees in chemistry and radiation biology. His doctoral studies at Imperial College in London and at Princeton University in the US examined the health effects of nuclear waste technologies. Dr Fairlie was Scientific Secretary to the UK Government's Committee Examining Radiation Risks of Internal Emitters (www.cerrie.org). Dr Fairlie remains a consultant to IPPNW, environment NGOs, and local governments in several countries.

Prof. Gordon MacKerron serves as Director of Science and Technology Policy Research at University of Sussex. He served as Director of Sussex Energy Group, SPRU (Science and Technology Policy Research), University of Sussex since April 2005, following four years as Associate Director, NERA Economic Consulting, London and an earlier career for over 20 years at SPRU. He is an economist specializing in energy and environmental economics, with degrees in economics from the Universities of Cambridge and Sussex. His academic career has specialized in the economics and policy issues of electricity and especially nuclear power, in which he has published and broadcast widely.

Ben Wealer is a research associate at the Workgroup for Economic and Infrastructure Policy (WIP) at Berlin Institute of Technology (TU Berlin), and guest researcher at DIW Berlin (German Institute for Economic Research) as well as a scholar of the Heinrich-Böll-Foundation. He holds a MSc in industrial engineering in the discipline of energy and resource management from the TU Berlin. His field of research is nuclear power economics with a focus on organizational models for decommissioning of nuclear power plants and radioactive waste management, economics of nuclear power plant new build, and the dual-use issues of nuclear power. Wealer is a long-term member of a research project on nuclear energy in Germany, Europe, and abroad run jointly by TU Berlin and DIW Berlin and he is the author—among others—of the first German independent decommissioning monitoring survey. Ben Wealer is also contributing author to the World Nuclear Industry Status Report 2018.

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1. Introduction

The basis for developing disposal strategies and responsible cost estimations as well as for monitoring is comprehensive, consistent and up-to-date information on nuclear waste. The more consistent and common the reporting methods, the more precise the forecasting of the amount of radioactive wastes (e.g. volumes, classes) will be and hence the more accurate the estimation of the need for disposal capacities and management routes. A common reporting basis would also allow for comparison between countries and for trend analysis.

Since detailed information on the global status of nuclear waste volumes is presently missing, the underlying waste units and classification schemes differ across countries and the prediction on costs for disposal stay often vague, the aim of this World Nuclear Waste Report (WNWR) is to fill this gap.

Its purpose is to provide an overview on nuclear waste and decommissioning data, disposal strategies and financial mechanisms and to highlight strategies for good practice and problems that have not yet been solved. The WNWR should allow for comparison across countries and, as we aim for a periodical format, for monitoring over time. Sources of uncertainty, like inconsistencies, contradictions and gaps in data, should be identified.

Even though there have been some dynamics in Europe in recent years, overall progress in the development of disposal strategies has been poor:

No country worldwide has to date developed and implemented a functioning and binding waste management strategy for all kinds of nuclear waste. Not yet a single final repository for high-level radioactive waste, such as spent fuel from nuclear power plants, is ready-made.

Finland is to date the only country in the world that has a permanent nuclear-waste repository under construction. Germany just started a new search for a final storage site and set-up the creation of a public fund to cover radioactive waste disposal. In France, the government has unilaterally opted for a deep geological disposal close to Bure in northeastern France, but since Andra is preparing the formal request to build the site, protests will not stop. In Sweden, the Environmental Court did not accept the regulator’s opinion on the copper canister concept and put the seemingly ready-made site and storage plan on hold in February 2018.

With power plants across the world approaching the end of their lives and countries entering nuclear phaseout, decommissioning and dismantling of nuclear power plants will become an increasingly important issue in the coming years, with important impacts on the amounts of radioactive waste generated. According to the WNISR 2018, the average duration of reactor decommissioning is around 19 years and is often longer than expected. In absence of a final disposal site, most of the high-level waste and spent fuel must be stored for many decades, challenging the safety-related requirements for interim storage facilities as well as the polluter pays principle.

This report aims to provide a comprehensive overview on the status of nuclear waste in Europe. It does so by pursuing the following steps:

- First, it outlines the origins and classifications of nuclear waste (chapter 2). What exactly constitutes a waste, as opposed to a useful substance or material, turns out not to be a matter of common sense. The chapter explains the origins of nuclear waste across the nuclear fuel chain, from uranium mining through to decommissioning and waste management. It then introduces international systems for classifying nuclear wastes, especially that of the influential IAEA as well as the EU.
- Next, it provides an overview of the volumes of four waste categories (chapter 3). Those include mining, operation, spent nuclear fuel, and decommissioning generated by nuclear

power plants used commercially for electricity generation in Europe. The text draws the data for different European national inventories from the official documents published under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

- Finally, the report will discuss the risks to the environment and human health from radioactive waste facilities and from their releases to the environment (chapter 4). It will focus on higher activity wastes and highlight potential dangers and problems that have not been resolved. The chapter will address the main risk drivers and will briefly describe the main hazards along the nuclear fuel chain, and attempt to quantify their risks using available data.

This report is the first of its kind. With its focus on Europe, the report aims only to start filling a wide-open gap. Outside the EU and Europe, there is even more variation in waste classification and practices by governments and agencies on nuclear waste. Social, political, technical and financial hurdles on the way to finding a sound long-term solution for these very dangerous wastes are high. So let us see where we stand.

2. Origins and Classification

This chapter outlines the origins and classifications of nuclear waste.[1] What exactly constitutes a waste, as opposed to a useful substance or material, turns out not to be a matter of common sense. For example, the UK Government guidelines on whether something is (any kind) of a waste, or not, are complex. A waste may, in this categorization, be something that the producer or owner intends to discard; or has low or negative economic value; or is hazardous (Defra 2012). However, in any of these cases recycling or re-use may be possible, turning the relevant substance into a 'non-waste'.

Applied in the nuclear field, the major issue is whether or not some substances produced by nuclear reactions are to be considered wastes or potential resources. The main dispute surrounds the products that arise when spent (used) fuel from nuclear reactors is 'reprocessed'. Reprocessing is where spent fuel is separated into its component parts: plutonium, uranium and various so-called fission products. Most reprocessing, for example that undertaken in France and the UK, has had a clear intention to re-use the separated plutonium, and possibly the reprocessed uranium, as fuel in future reactors. Moreover, significant quantities of plutonium have been re-used in this way.

However, plutonium may qualify as a waste by virtue of its indisputably hazardous nature and/or its low or negative economic value. Whether or not plutonium and reprocessed uranium are categorized as a waste or resource varies by country and over time. For example in the UK in the 1950s, official economic appraisals of nuclear projects included a 'plutonium credit'. It was intended to reflect the then-expected value of separated plutonium as a future nuclear fuel. 50 years later, this early optimism had abated. By the 2000s, plutonium was classified as a 'zero-valued asset', a category puzzling to most economists. By the 2010s, the status of plutonium had become ambiguous. The relevant public agency, the UK's Nuclear Decommissioning Authority, declared that its preferred option was to re-use plutonium as a component of future nuclear fuel (NDA 2014). However, it also argued that a small quantity of contaminated plutonium would have to be treated as waste and that if re-use turned out to be unfeasible for some reason, the immobilisation planned for the contaminated plutonium might be extended to the whole stockpile, at which point plutonium would unambiguously be a waste. In any event the net cost of managing plutonium in the UK is expected to be at least £3bn (NDA 2010).

While plutonium may appear as a resource in the short term it is almost always recycled only once, so that plutonium re-use simply leads to another form of spent fuel – one that is more radioactive and difficult to manage than the spent fuel that is produced using uranium-only fuel. In other words reprocessing both postpones the waste issue and makes it more complex.

The point here is not to adjudicate on the status of plutonium or other materials. The point is rather to recognize that the issue of managing the various products of nuclear reactions, whether formally wastes or not, is politically and socially contentious and involves potentially high hazards. While this chapter covers the range of waste products resulting from nuclear reactions, the special importance of spent fuel is that its radioactivity is 100 million times greater than the radioactivity of fresh fuel. It is therefore necessary to give particular attention to spent fuel wastes.

2.1 Coverage

The question arises of whether it is useful to describe and classify all products of nuclear reactions. This chapter does not do so, but instead concentrates on the relatively higher activity wastes that large-scale civilian production of nuclear energy for power production gives rise to. The so-called low-level wastes from power production are not excluded from scope but need little discussion, despite their

[1] In some discussions, the term 'radioactive' waste is used and this is essentially interchangeable with the idea of nuclear waste.

relatively high volumes. This is because both the level of hazard is much lower and mostly there are well-established management routes.

What are the other categories of nuclear waste and why are they excluded? The other uses of nuclear technology are mainly for medical and military purposes. The waste products from these activities are outside the scope of this report for two reasons: first in the medical isotope case, waste quantities are small and there are well-established routes for management; second, in the military case quantities are also small (relative to power production), and while there are no well-established management routes, data are limited and most of the hazardous materials produced are the same as for civilian power production.

Conversely, the reasons to concentrate here on the so-called higher activity wastes from nuclear power production are clear: hazards are high because the radioactivity levels contained in spent fuel are immensely greater than anywhere else in nuclear activities; and as yet there are no long-term management routes established for these wastes anywhere in the world. Because of these factors, problems of managing wastes from nuclear power production are major political issues.

2.2 Types of waste: the nuclear fuel chain

Nuclear wastes arise ('arisings' is a term widely used in this context) at all stages of the nuclear fuel chain – sometimes also referred to as the nuclear fuel 'cycle'. While it is possible to use thorium as a nuclear fuel, in practice uranium is overwhelmingly the dominant source of fuel for nuclear power. All the wastes described here ultimately stem from the ways in which uranium is used in electricity production. This also means that there is no consideration of the types of waste that might arise if nuclear fusion were ever a serious power source.

The sequential stages of the nuclear fuel chain are as follows (see Figure 1 for an extended view):

1. Uranium mining, milling, enrichment and fuel fabrication (these activities are often referred to as the 'front end' of the fuel chain)
2. Irradiation of nuclear fuel in reactors
3. Management of spent fuel, whether or not reprocessed
4. Reactor decommissioning (stages 3 and 4 are often known as the 'back end' of the chain)

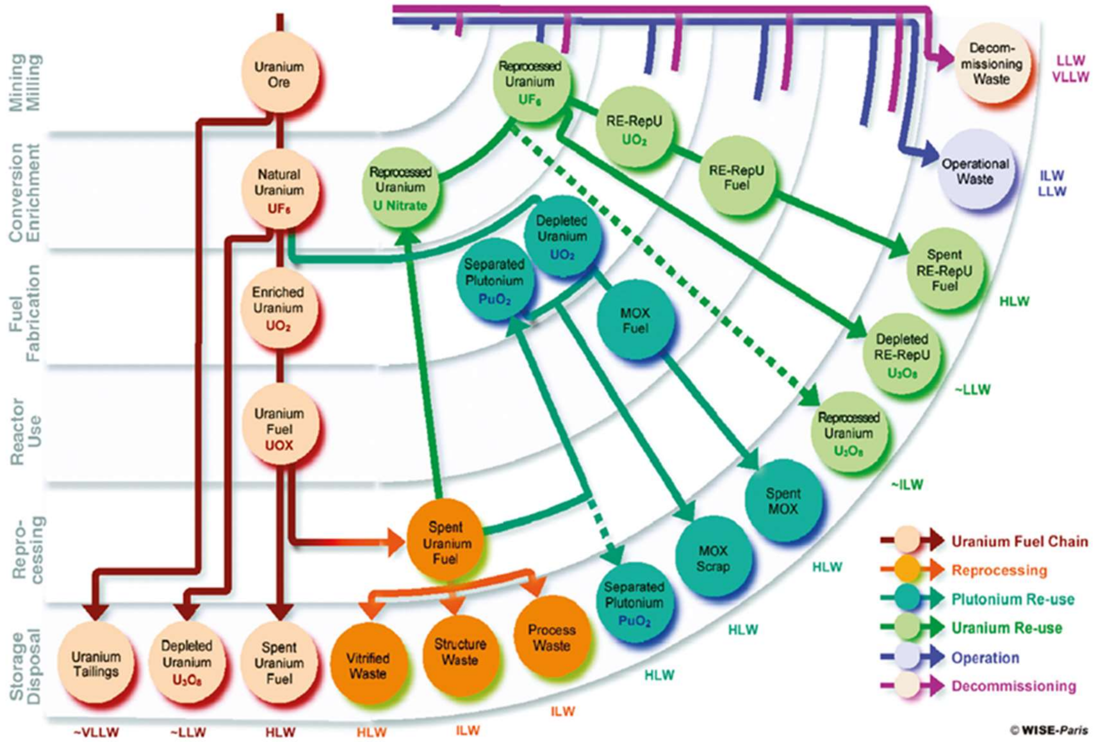

Figure 4.12 | The nuclear fuel chain. Source: WISE-Paris.

Figure 2.1: The nuclear fuel chain
Source: Wise-Paris

The wastes that arise at these various stages can be gaseous, liquid or solid. For some forms of gaseous wastes, e.g. radon in underground uranium mines, measurement is rarely attempted and – while gases like radon are extremely harmful – management consists in reducing exposures rather than measuring or capturing existing levels. Solid forms of waste are generally the most stable and easiest to manage and a substantial aim in policy is therefore often to convert less stable waste forms into more manageable solid forms. For example reprocessing of spent fuel produces a waste stream of boiling and radioactive nitric acid, which is then subject to evaporation and turned into a vitrified (glass) product.

Taking each of the four stages of the nuclear fuel cycle in turn:

2.2.1 Uranium mining, milling, processing and fuel fabrication

The most important waste and major health risk derives from the existence of radon gas in underground uranium mines. Radon is an alpha emitter and decays to polonium, which has similar characteristics. If inhaled into the lungs radon and polonium cause great damage. Other sources of radioactivity from any kind of mining in uranium mining of any kind is the existence of uranium, which decays into radon, in mine 'tailings' – usually waste heaps of discarded rock material from mining operations. Because these wastes are gaseous, they are not directly captured. The other stages of uranium processing including fuel fabrication produce very limited amounts of wastes.

2.2.2 Fuel irradiation

In the process of fuel irradiation significant quantities of waste are generated as 'operational wastes', broadly from maintenance, refuelling and transport of spent fuel. These include the following: debris from fuel elements including steel and various alloys; components used in maintenance, which are

often highly active; contaminated liquid wastes and sludges; resins and filters; and clothing and equipment generally at low levels of activity.

2.2.3 Management of spent fuel

Irradiation of uranium fuel is the area of nuclear technology that produces by far the largest amount of radioactivity. This is because irradiation produces a variety of fission products and so-called minor actinides that multiply the radioactivity in the original uranium fuel by more than 100 million times. Management of spent fuel, whether via reprocessing or regarding it as a waste, is therefore by a long distance the most important waste management activity arising from the nuclear fuel cycle. Initially spent fuel has to be stored under water to allow some of the decay heat to reduce

If fuel is reprocessed, then significant quantities of further low and intermediate level wastes are created, meaning that the total volume of waste to be managed (though not the total activity) is much greater than if the spent fuel is treated as a waste. The residual fission products and minor actinides – after uranium and plutonium are separated – are then evaporated and converted to solids by a vitrification process, again prior to final disposal. In addition, there will be significant costs of decommissioning reprocessing plants. Where spent fuel is treated directly as a waste it is in principle encapsulated prior to direct disposal.

2.2.4 Reactor (and fuel cycle facility) decommissioning

To date very little full-scale decommissioning of reactors or other nuclear structures (i.e. complete demolition of structures) has taken place, even where reactors have been closed for decades (WNSIR 2018). One reason for delay – other than the obvious one of postponed costs – is that some radionuclides contained in these structures have relatively short half-lives and so access for demolition will be easier if operations are postponed. Reactor structures contain significant quantities of radioactivity in their cores, as many components are contaminated by radioactivity from the fuel that has been irradiated within them. Large quantities of materials like steel and concrete therefore constitute radioactive wastes, though their total activity levels are small compared to the activity in the spent fuel.

2.3. Classification systems

Despite attempts over some years to get agreement within the EU on a consistent classification system across member states for nuclear wastes (ILW Repository Ltd 2016), there remain quite different classification systems across the EU, some of which are summarised below.

However, the International Atomic Energy Agency (the UN body that covers all UN member states) provides a broad framework of classification (IAEA 2009). This constitutes a default position, and countries without nuclear power programmes almost universally adopt it directly. For countries with significant nuclear programmes, their national classifications of wastes sometimes refer back to the IAEA system for comparative purposes.

The IAEA identifies six types of waste, focusing mainly on solid wastes. There have been limited disputes over the management strategies for the first four categories of waste described below (up to and including Low Level Waste) - in most countries there are in place long-term management strategies for wastes that fall into these categories.

The main issues where political controversies arise – where there are not yet any agreed and operational long term management facilities anywhere in the world – concern the categories of Intermediate Level and, especially, High Level Waste. In relating waste categories to management options, the IAEA assumes that these options will always take the form of various kinds of land-based

disposal, -at the surface, or sub-surface, including disposal in deep geological repositories. The IAEA (2009) defines the six categories as follows.

2.3.1 Exempt

This category involves such small concentrations of radionuclides that there is no need, in the view of the IAEA, for any specific radiation protection measures. The IAEA safety guide () suggests that these are wastes suitable for 'exemption, exclusion or clearance'. This in principle allows such material to be transferred from one State to another without any form of regulatory oversight.

2.3.2 Very short-lived waste (VSLW)

In this category there are radionuclides of very short half-life and these are often stored until their activity levels allow them to be re-categorised as exempt. Several wastes from industrial and medical applications fall into this category and some gaseous and liquid wastes are categorised as VSLW. In general terms, storage for decay is 'applied for radionuclides with half-lives of the order of 100 days or less'

2.3.3 Very low level waste (VLLW)

Within this category there are substantial amounts of waste stemming from the operation and decommissioning of nuclear facilities, as well as some wastes arising from the mining and processing of uranium ores. Managing these wastes, unlike those in the two categories above, require management that takes full account of radiation protection and safety. Characteristic activity levels of radionuclides that fall within this category are between ten and a hundred times those of levels for exempt wastes. The IAEA suggests that safe management for these wastes will involve engineered surface landfill facilities, requiring both active and passive institutional controls over a significant but unspecified period in the future.

2.3.4 Low level waste (LLW)

LLW is defined as waste suitable for near surface disposal, where such disposal sites meet the criterion that there will be robust containment and isolation for what the IAEA describes as 'limited periods of time'. However, these limited periods of time turn out to be 'up to a few hundred years'. In a number of States the assumption is made that institutional controls can be relied on for periods up to 300 years, though for wastes from mining and processing of uranium, activity levels fall slowly and so control needs to 'postulated' for longer periods than 300 years. The assumption that institutional control can be assumed for up to 300 years (or in some cases, as above, longer) is essentially arbitrary.

This category covers a very wide range of wastes and may contain low levels of long-lived radionuclides. Typical materials that fall into the LLW category include clothing, packaging material, soil, and significant products of reactor decommissioning including steel and piping. Depending on the exact composition of the wastes, the IAEA recommends disposal practices that vary between surface storage to burial at depths of up to 30 meters. Precise boundaries between LLW and the next category (Intermediate Level Waste or ILW) are not provided generically as much depends on the characteristics of different kinds of disposal facility designs. For the foregoing waste categories, there are, for most countries, operational facilities to manage these wastes. The same is not the case for the final two categories, outlined below.

2.3.5 Intermediate Level Waste (ILW)

These are wastes that contain relatively large quantities of long-lived radionuclides, and there is a consequent need to engineer facilities that do not depend on institutional controls. However, ILW does not produce heat from radioactive decay and so does not need to take heat into account in its management. Characteristic sources of ILW are nuclear fuel cladding, some reactor components when decommissioning takes place, and various sludges from treating radioactive liquid effluents. In

addition, where spent fuel is reprocessed, significant volumes of ILW are also created. In many cases, these wastes are packaged into cement-based materials and enclosed within large drums or containers, often of steel. The IAEA recommends disposal at depths of between a few tens and a few hundreds of meters below ground in sites where natural geological barriers and engineered barriers have the potential to achieve long periods of isolation from the surface environment.

2.3.6 High Level Waste (HLW)

High-level waste contains large concentrations of both short-lived and long-lives radionuclides. It is also defined as waste that generates significant quantities of heat from radioactive decay, and will continue to generate heat for long periods into the future. This means that dissipation of heat has to be taken into account in designing management routes. The implication for disposal is that deep geological disposal is necessary, in stable geological formations, and with the additional use of multiple engineered barriers to try and ensure that the chances of radioactivity returning to the biosphere are vanishingly small. Essentially HLW arises from the irradiation of nuclear fuel, and is managed either as spent fuel, where this is treated directly as waste, or as the initially liquid products of reprocessing, including plutonium and various actinides and fission products.

2.3.7 Waste volumes and activity

The total quantities and activity levels of these various categories of waste are inversely related. In other words the lower level wastes are produced in large volumes but contribute very little to the overall levels of radioactivity (and therefore potential harm). Conversely, high-level wastes are present in very small volumes but contribute the vast bulk of radioactivity. This is not a surprising result, remembering that the radioactivity in spent fuel – from which HLW is derived – is more than 100 million times greater than the radioactivity in fresh uranium fuel.

An illustration of this comes from the waste inventory that the UK Committee on Radioactive Waste Management considered when it examined UK nuclear waste policy in the early 2000s (CoRWM 2006: 20). High level wastes (spent fuel, plus HLW separated in reprocessing) amounted to 96.8% of all the inventory's radioactivity but only 2.6% of its volume. ILW by contrast contained only 3.2% of the total radioactivity, but 97.4% of the volume. LLW occupied much larger volume than ILW but its contribution to total activity level was so small (less than 0.001%) that it does not really register in these calculations.

2.4 Classification recommended by the EU

The EU has regulatory powers across all member states in the area. Its 2011 Radioactive Waste Management and Decommissioning Directive (EU 2011) set out generic targets for waste management including a timetable. It has no powers to require a common process of waste classification across member states but did translate member state data on wastes into a common system of its own based on the IAEA categories described above. However, it did, as far back as 1999, and amended in 2008, publish recommendations for waste classification systems across all member states, based on the IAEA system (EC 1999). This system included the following categories:

- Transition wastes (equivalent to short-lived LLW)
- Very low level wastes
- Short-lived (half-life of less than 31 years) low level and intermediate level wastes
- Long-lived (half-life longer than 31 years) low and intermediate level wastes
- High level wastes (heat generating)

However, within the EU no country has exactly followed this recommended system, although France (see below) and the Czech Republic have come close, especially in relation to the distinction between short- and long-lived wastes.

To exemplify the variety of national classification systems used in the EU, four systems are described below. These have been chosen according to two criteria: that there are substantial volumes of waste at all activity levels; and they illustrate the diversity of approaches that different national Governments take to classification issues. There are of course many other systems in the EU, none of them exactly the same as any other. Outside the EU, there is even more variation in waste classification. Thus, a brief description follows of another national system of a country with substantial waste volumes: the United States. It illustrates the even greater variety of classification systems outside the EU.

2.5 National systems of waste classification

2.5.1 Germany

The German system of classification is in outline relatively simple. It distinguishes two main categories based on requirements for disposal: heat-generating wastes and all others, described as wastes with negligible heat generation (OECD/NEA 2005). The first category corresponds to the IAEA category of HLW (including both wastes from reprocessing spent fuel, as well as spent fuel itself), while the second category is essentially a combination of the ILW and LLW categories from the IAEA. Policy in Germany is to dispose of both categories of waste in deep geological repositories, but in different sites needing different design characteristics.

2.5.2 France

Then French system is more complex than the German. It uses five main categories, ignoring VSLW, which corresponds to the same category in the IAEA scheme (ASN undated). While, apart from the category of VSLW, the IAEA system is one-dimensional, concentrating on activity levels, the French system is more comprehensively two-dimensional. It adds the criterion of the time taken in each category of waste to reach half-lives (when the level of activity has decayed to half its original level). The categories are:

- High Level Waste – heat generating
- Intermediate Level Waste (long-lived)
- Low Level Waste (long-lived)
- Low and Intermediate Level Waste (short-lived)
- Very Low Level Waste

In this system, only the first and last (VLLW and HLW) categories broadly correspond to the IAEA classification. In relation to LLW and ILW the French system takes account of the longevity of the potential harm represented by different types of waste as well as the initial level of activity, and so creates further distinctions than the IAEA in both ILW and LLW. The French system categorises wastes as short-lived if their half-lives are predominantly shorter than 31 years, and as long-lived if their half-life exceeds 31 years. This second dimension – the half-life – is related to French policy for disposal. Thus while HLW and ILW (long-lived) are both expected to go to deep geological repositories, ILW (short-lived) is expected to go to surface disposal, while LLW (LL) is expected to be managed in sub-surface facilities.

2.5.3 The UK

Compared to France and Germany, the UK's system is closely aligned to that of the IAEA (LLW Repository Ltd 2016). Its four categories correspond to the final four of those outlined above in relation to the IAEA and are therefore:

- HLW - heat generating, mostly products of reprocessing, plus spent fuel
- ILW
- LLW
- VLLW

While these are the main operational waste categories in the UK, there is also another distinction, closely related to current disposal options. The distinction is between:

- Higher activity wastes, defined as HLW, ILW and that part of LLW not currently disposable. At present, there are no long-term management routes for any of these wastes.
- Lower activity wastes, which are the bulk of LLW plus VLLW, all of which are currently disposed in engineered surface facilities.

2.5.4 Czech Republic

The Czech Republic has the largest volumes of nuclear wastes of any of the more recent member states of the EU. Its classification system is similar to that of France and to the EU recommendations. Its categorisation is as follows:

- HLW – heat generating
- Long-lived ILW and LLW (half-life ovr 30 years)
- Short-lived ILW and LLW (half-life under 30 years and with limited long-term alpha nuclides)
- Transient wastes - equivalent to Very Short Lived Waste in the IAEA scheme

2.5.5 United States

The USA has two quite distinct sets of categories: one for military-origin wastes (which is ignored here) and the other for civilian-origin wastes. The US system recognises five categories of waste (Cochran 2016):

- HLW – products of the reprocessing of spent fuel
- Spent fuel
- Transuranic wastes
- Low level wastes, which are then divided into four further categories
- By-product material

The first two categories (HLW and spent fuel) are, in IAEA terms, HLW. But beyond these first two categories the other three are quite different from IAEA categories. The US LLW includes material that under IAEA classification would count as VLLW and VSLW as the US does not recognise any radioactive wastes that are exempt from controls. The four categories of LLW relate to the extent to which the particular wastes are related to protection of the public and for inadvertent intruders to a waste site. Finally, by-product material is a miscellaneous grouping of reactor or fuel fabrication material (other than uranium and plutonium) and tailings from uranium mining.

2.6 Summary

The chapter explained the origins of nuclear waste across the nuclear fuel chain, from uranium mining through to decommissioning and waste management. It then introduced international systems for classifying nuclear wastes, especially that of the influential IAEA as well as the EU.

The analysis reveals that EU member states differ significantly in their practises on nuclear wastes. First, there is disagreement about whether spent fuel and some of its potential separated products (plutonium and uranium) are a waste or a resource. Second, there are quite significant divergences in the categorisations of waste, with no two countries having identical systems. While all agree on the category of heat-generating (high level) wastes, there are many alternative ways of characterising other nuclear waste streams. These differences signify a lack of transparency in the classification process.

Despite authoritative guidance from the IAEA and a largely unsuccessful EU attempt to harmonise waste classification systems for member states, there are substantial differences between European classification systems, and even more variety when considering non-EU countries. While there is universal agreement on the category of high-level waste (HLW), distinguished by the need to manage decay heat, there is sharp disagreement on whether spent fuel (the source of high level waste) should even be classified as a waste. Several countries regard spent fuel as waste, to be disposed directly, while others regard it – once reprocessing separates plutonium and uranium – as a resource. Another common feature in the HLW category is that there is as yet no available long-term management route for HLW, though there is official consensus that deep geological disposal is the best way forward.

Below the HLW category there is no consensus about classification. The main differences are between those countries that draw a distinction between short-lived wastes either intermediate or low level, and those, which do not. Some systems are based on the origins of waste, some on potential or actual disposal sites, and yet others on activity and half-lives. This is necessarily a source of confusion and there is an open question about whether – for the sake of both transparency and safe management – existing classification systems should be amended, or a new system developed.

3. Volumes of Waste

Despite the lack of adequate disposal facilities, the volumes of nuclear waste in Europe are increasing steadily (European Commission 2017). This chapter provides an overview of the volumes of nuclear waste in Europe (the EU Member States, Ukraine, Switzerland, and the Russian Federation) in four categories: mining, operation, spent nuclear fuel, and decommissioning generated by nuclear power plants used commercially for electricity generation. The text draws its data from documents published by national governments and regulatory agencies (as listed in Annex II) and other responsible governmental bodies under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.[2]

3.1 Uranium Mining

In order to use uranium as a fuel for electricity generation in nuclear power plants, uranium—a natural resource—has to undergo several processing stages. First, the uranium ore has to be mined, separated from waste material, and milled, resulting in yellow cake; the latter is then converted to uranium hexafluoride, then enriched, and fabricated into fuel elements. All these processes attributed to the front-end of the fuel cycle produce radioactive wastes. The first wastes that emerge are the tailings (excavated rocks to access the uranium ore) that have remained at the site, in some cases they were stockpiled (in heaps) to fill open-cast mines or to redevelop areas. Among the European Member states, only some minor quantities of uranium are currently exploited (e.g. Czech Republic, Romania) and most fuel is imported—around 85% of the world's mined uranium is supplied by six countries, i.e. Canada, Kazakhstan, Australia, Niger, Namibia, and Russia (Mendelevitch and Thien Dang 2016). This creates large amount of wastes in the respective export countries.

Although the mining of uranium ore was to a low extent in France, the former French uranium mining industry still generated 50 million tons of mining residues, spread over 17 disposal sites in former mine works (République Francaise 2017, 67). Much larger quantities of uranium ore had been formerly mined in the former GDR (Neumann 2010, 7). As in most cases, the rehabilitation of the residue disposal sites consisted only in installing a solid cover over the residues.

Table gives an overview of the wastes from uranium mining in the European Union.

[2] The National Reports can be found on the following IAEA page: https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste/documents?keywords=&type=4797&language=All&field_extres_date_value%5Bvalue%5D%5Byear%5D=&country=All If these reports are not publically available, a second possible source will be the databases of the International Atomic Energy and the Nuclear Energy Agency of the OECD.

Country	Waste from Radium and Uranium production	Storage Site
Belgium	95,000 m^3	3 storage facilities (UMTRAP, Bankloop, "third")
Bulgaria	5.8 million m^3	Buhovo-1 and Buhovo-2 tailings ponds
Czech Republic	n.a.	Straz, Dolni Rozinka
Finland	n.a.	Eno Askola
France	50 million tonnes	Spread over 17 dipsoal sites in fomer mine works
Germany	46.5 million tonnes of heaps and 4.7 million m^3 of tailings	Wismut (in recultivation)
Romania	9.8 million m^3	CNU Feldioara, CNU Suceava, CNU Stei (Bihor), CNU Oravita (Banat)
Slovenia	1.6 million m^3	Zirovski
Spain	88.1 million tonnes	Salamaca, Badajoz, Jaen

Table 1: Waste from Radium and Uranium production
Source: Own compilation based on the reports published under the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management.

Services for commercial conversion of yellow cake to uranium hexafluoride are offered by plants (centrifuges) in France and Russia (as well as Canada, China, and the USA). Commercial enrichment services are provided by England, France, Germany, the Netherlands, Russia (as well as Japan and the USA)(Mendelevitch and Thien Dang 2016). Uranium-containing waste is generated in both stages. The most hazardous as well as the plants with the most wastes are at Capenhurst (Great Britain), Almelo (The Netherlands), Gronau (Germany) and Tricastin (France); in the past, the operator companies in France, Germany and The Netherlands transported the byproduct, the depleted UF6, to Russia (more than 10,000 t per year), where the large part of the UF6 remained. Now the companies operating the enrichment plants in the EU have to keep the depleted UF6 (Neumann 2010). In Germany, the the expected waste package volume of waste resulting from uranium enrichment is up to 100,000 m^3 of depleted uranium – only in the case that there will be no further reutilization (NEA 2016, 5).

3.2 Operational Wastes

The operation of nuclear power plants for electricity generation produces different kinds of radioactive wastes in different kinds of physical states, of which the major part is low and intermediate level waste (LILW). The IAEA (2007) classifies operational wastes into two main categories: unconditioned (as-generated) and conditioned operational waste. For unconditioned operational wastes an indication on the physical state is important, i.e. liquid or solid.[3] Unconditioned waste can be *raw waste*, i.e. waste in its original form (liquid or solid and is often listed in tons (or mega gram (Mg)) of heavy metal (HM) for solids, and m^3 for liquid wastes. Another category is *pre-treated waste*, waste which has undergone some form of preconditioning and is often measured in tons for solids and m^3 for liquid wastes. Naturally, the generation of waste volumes depends on many factors, e.g. the deployed reactor technology, or the age of the reactor. Applying the proposed generation rate for different reactor types

[3] Solid wastes are for example protective clothing, replaced plant components, or insulation material. Liquid wastes are for example cooling water contamination, oils, vaporizer concentrates, filter substances, or sludge, which forms when solid matter collects as sediment at the bottom of pumps (IAEA 2007a).

(e.g., 250 m^3 for PWR and 500 m^3 for BWR[4]) by the IAEA (2007) to the European operational reactors (excluding the Russian fast breeders and the light-water gas-cooled RBMK reactors) leads to an estimated radioactive waste inventory of at least 1,300,000 m^3 of unconditioned operational LILW (see **Table 5**). This of course us a very conservative estimate. A full estimate would need to include waste from already shut down reactors, which are not included here.

To bring the different wastes into a stable and immobilized form to make it suitable for transportation, storage, or eventually final disposal the waste needs to be conditioned; compaction is also applied in order to minimize the waste volumes; compaction can be a part of conditioning but does not have to be.[5] *Stored waste* is generally conditioned in drums, storage, transport, or disposal casks and measured in m^3, or number of casks/drums. Estimations for the generation of annual conditioned LILW per reactor vary among the observed countries. Germany, for instance, estimates 45 m^3 of conditioned LILW for its light-water reactors (Federal Republic of Germany 2018, 85), while France estimates 78 m^3 per reactor for its PWRs (Neumann 2010). For illustration, applying a conservative average annual generation rate of 60 m^3 per reactor to the total estimated lifetime of the European nuclear power plants would lead to 575,100 m^3 of (only) operational LILW (**Figure 1**). France would have to cope with more than a third of all European operational LILW, Russia with a fifth. The top five countries (France 36%, Russia 19%, Ukraine 8%, U.K. 6%, and Sweden 5%) account for nearly 75% of the entire European operational LILW.

A last waste category is *disposed waste.* As until today only a few countries have installed operational disposal facilities for LILW (e.g. CIRES in France, Asse II in Germany), the amounts of disposed of radioactive wastes are still small. Disposed waste is often measured in m^3, or waste packages.

[4] 600 m^3 for VVER, 200 m^3 for PHWR, and 650 m^3 for AGR.

[5] For more details on the waste production techniques, see Homberg, Pavageau, and Schneider (1997).

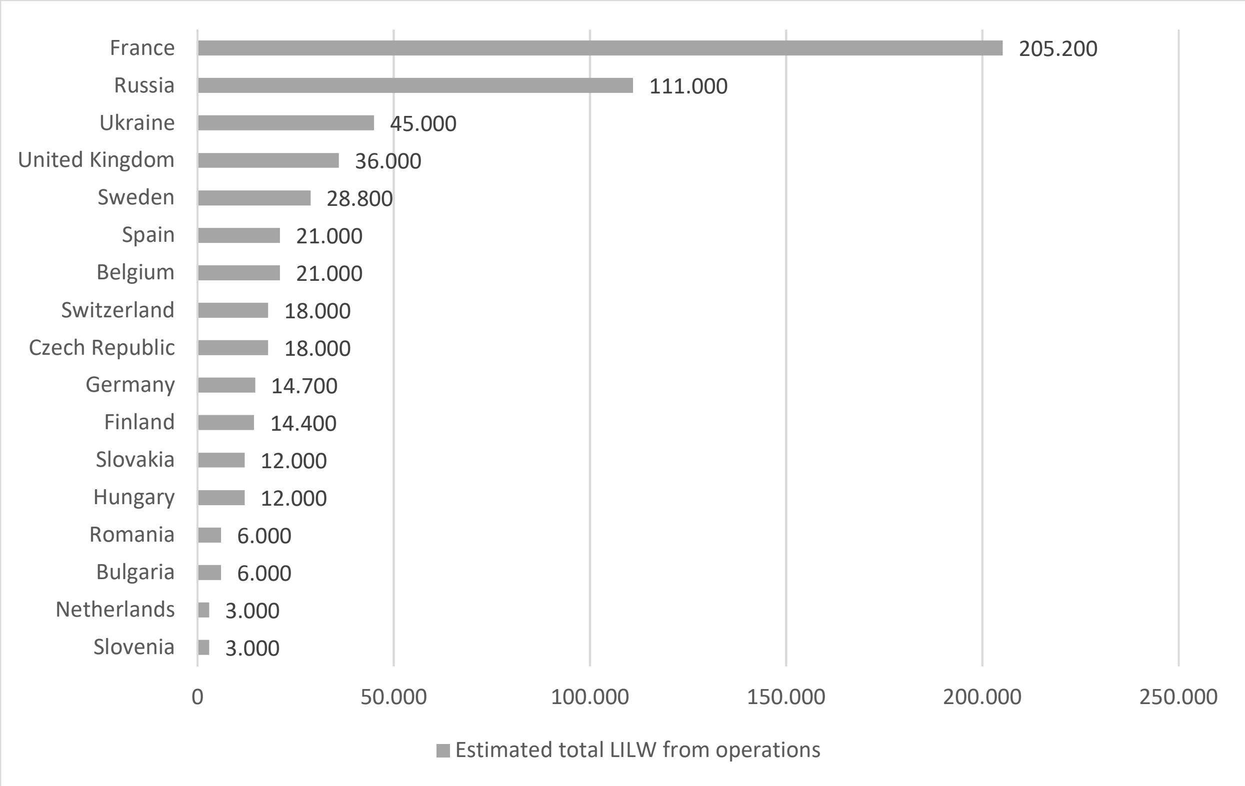

Figure 1: Estimate of total future conditioned volumes of operational LILW in Europe

Source: Own compilation based on Schneider et al. (2018) and IAEA (2007b).

3.2.1 Legacy Wastes

The above mentioned different inventory approaches render it difficult to compare the volume of legacy wastes in the different countries, as operational wastes are stored in different physical states (e.g. liquid, solid, pre-compressing) or they are already conditioned, compacted, or disposed of. Sometimes the wastes are clustered into different categories, i.e. LLW and ILW or LILW or are still in other different forms. The most striking case would be Slovakia, where most of the information (e.g. waste volumes in pieces, drums, pallets…) does not allow any classification of volumes. For simplicity, the waste volumes in **Table 1** are clustered together as LILW, where the information of the physical state was given, this was respected. **Table 1** gives information about the amounts of LILW in interim storage, the already disposed of amounts, and the total produced LILW. Altogether around 2,404,598 m^3 of LILW has already been produced in the European Union, while 82 percent or 1,963,763 m^3 have already been disposed of. This actual produced amount of LILW is already the double amount of unconditioned LILW, based on the IAEA assumptions. The different national reports don't always give details about the origin of the waste; i.e. if the cited LILW volumes stem only from operations or if some decommissioning waste volumes are included.

Country	Liquid LILW [m^3]	Solid LILW [m^3]	LILW in interim storage [m^3]	Disposed of LILW [m^3]	Total produced LILW [m^3]	Disposed Share
United Kingdom	0	0	129,100	941,730	1,070,830	88%
France	0	0	154,200	843,000	997,200	85%
Germany	0	0	45,206	84,131	129,337	65%
Lithuania	16,934	26,900	43,834	0	43,834	0%

Country	Liquid LILW [m³]	Solid LILW [m³]	LILW in interim storage [m³]	Disposed of LILW [m³]	Total produced LILW [m³]	Disposed Share
Sweden	0	0	2,301	37,841	40,142	94%
Spain	0	0	6,748	32,198	38,946	83%
Belgium	0	0	17,302	0	17,302	0%
Hungary	8,131	2,490	10,621	5,776	16,397	35%
Czech Republic	1,487	708	2,195	11,520	13,715	84%
Bulgaria	6,297	5,562	11,859	0	11,859	0%
Netherlands	0	0	11,109	0	11,109	0%
Finland	0	0	1,970	7,567	9,537	79%
Slovenia	0	0	3,408	0	3,408	0%
Romania	0	0	982	0	982	0%
Total	**-**	**-**	**440,835**	**1,963,763**	**2,404,598**	**82%**

Table 1: Inventory of stored and disposed of volumes of LILW, as of 31.12.2016

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

Even though, the share of disposed waste seems high, 91 percent of the disposed waste was disposed only in the U.K. and France, while only less than half of the observed countries even have installed disposal facilities for LILW (i.e. U.K., France, Spain, Hungary, Finland, Czech Republic, Sweden, and Germany). In Germany the two geological disposal facilities for LILW are shut down and waste is currently stored on the site of the nuclear power plants. In the Asse II mine in Lower Saxony around 47,000 m³ of LILW in 125,787 casks have been disposed of between 1967 and 1978. However, there has been a continuous inflow of groundwater from the overburden into the mine and in 2010 it was announced that the best closure option would be the complete retrieval of the waste. There exists no disposal pathway for the up to 220,000 m³ mixtures of radioactive waste and salt, which should be retrieved from the disposal facility (Kommission Lagerung hoch radioaktiver Abrallstoffe 2016, 27).

Figure 2 shows the amounts of produced LILW, both currently in interim storage as well as already disposed of LILW. The U.K. accounts for one third of the produced LILW in the European Union. Altogether, the three major nuclear countries France, the UK, and Germany account for 75 percent of the "European Union waste". France and the UK, each (!) have disposed the double amount of LILW that is currently in interim storage in the EU. Even though, the top three countries, U.K., France, Germany have already disposed large amounts of LILW, they still account for 75 percent of LILW currently in interim storage that awaits disposal facilities. As it is (in 2018) the case with Germany, Lithuania (4th with 10 percent of the European share) has currently no operational disposal facility and the waste is stored on-site. **Figure 3** gives the shares of LILW in interim storage by country (for the volumes of waste see **Table 1**).

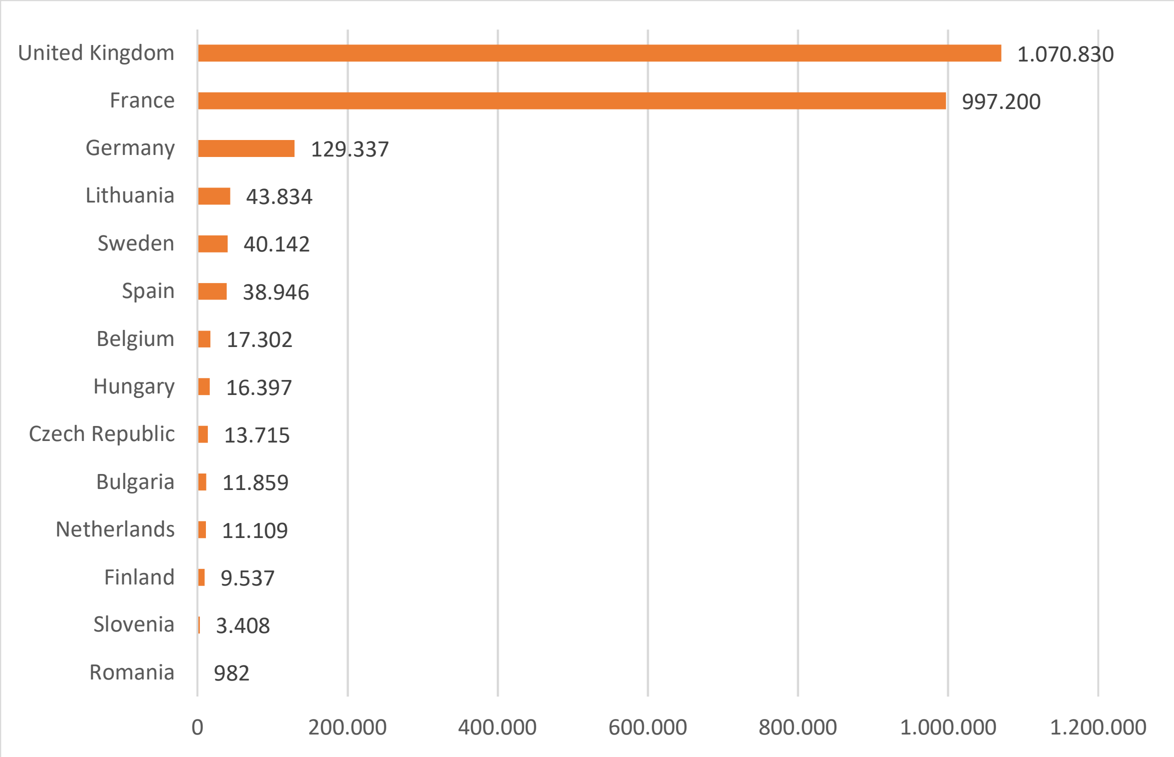

Figure 2: Produced LILW in m³ the European Union by country, as of 31.12.2016

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

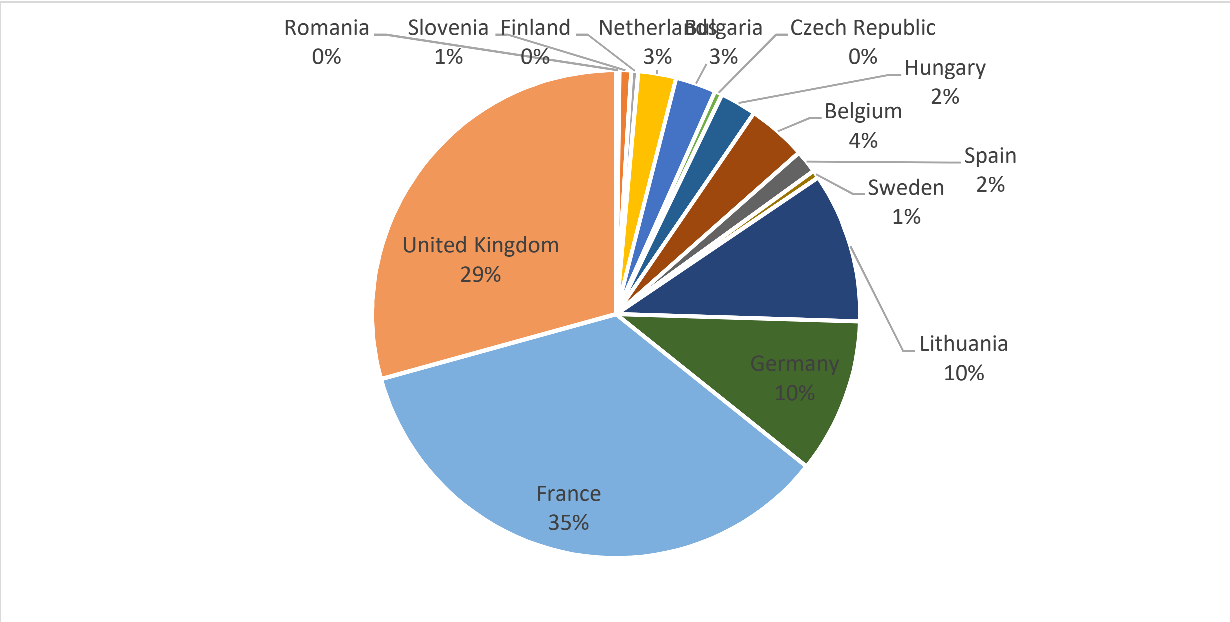

Figure 3: LILW in interim storage in Europe by share, as of 31.12.2016

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

3.3 Spent Nuclear Fuel (SNF)

About 370,000 t HM of spent nuclear fuel (SNF) have been generated worldwide since connecting the first reactor to the grid, roughly a third of it, 124,000 t HM, has been reprocessed (IAEA 2018, 35, 36). In some European countries reprocessing is still part of the waste management concept (e.g. France, Russia), while some countries have abandoned it (e.g. Germany, Switzerland). Others have never practiced it (e.g. Sweden, Finland). Worldwide only a handful of countries offer commercial reprocessing services; operational reprocessing facilities are France (La Hague), the UK (Sellafield THORP), Russia, and Japan. The IAEA (2007) estimates that the operation of a 1 GW_e light-water reactor generates around 30 to 50 t HM of SNF. This data would indicate that approximately 11,000 to 18,000 tons of SNF are produced annually by the 363 GW_e of installed capacity (Schneider et al. 2018, 17). The IAEA estimates that reprocessing would convert this amount into 15 m^3 of vitrified HLW(IAEA 2007b, 12). This conservative estimate of course does not include the vast amounts of depleted uranium and plutonium.

3.3.1 Interim Storage of Spent Fuel

In most cases, the inventory of spent fuel is given in tons of heavy metal (t HM or Mg HM) as well as in numbers of fuel assemblies (FA). In the cases of Belgium (only the 2009 Report contained the latest SNF inventory), Hungary, Lithuania, and Slovakia only the number of fuel assemblies was given, here the weight was calculated by assuming the weight per assembly (see Table 6 in the Annexes). **Figure 4** shows the SNF inventory (this does not include the amount of reprocessed SNF) in Europe. There is currently around 56,000 t HM of spent nuclear fuel stored in various forms across the Member States. France accounts for 25 percent of the current SNF inventory in the European Union, followed by Germany (15 percent) and U.K. (14%); altogether these three countries are accountable for over 50 percent of the European SNF inventory. The top five countries (including Sweden with 12 percent and Spain with 9 percent) account for 75 percent of the inventory. Although, France and the U.K. reprocess their SNF, they still have the largest amount of SNF stored in the EU. **Figure 5** gives an overview of the share of the nuclear waste by country. Only five countries account for 75 percent of all the SNF inventory: France (25 percent), Germany (15 percent), UK (14 percent), Sweden (12 percent), and Spain (9 percent). The top three account for more than 50 percent although all three practiced reprocessing and hence reduced the amount of stored SNF - although Germany abandoned it in 2004.

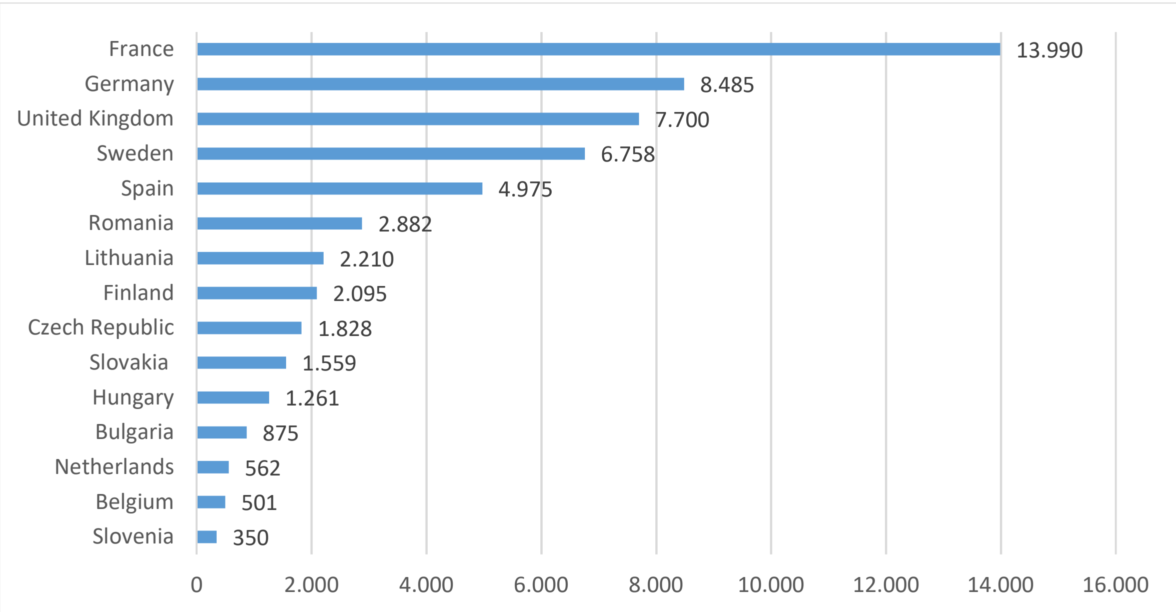

Figure 4: Reported SNF inventory in Europe by country, as of 31.12.2016

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

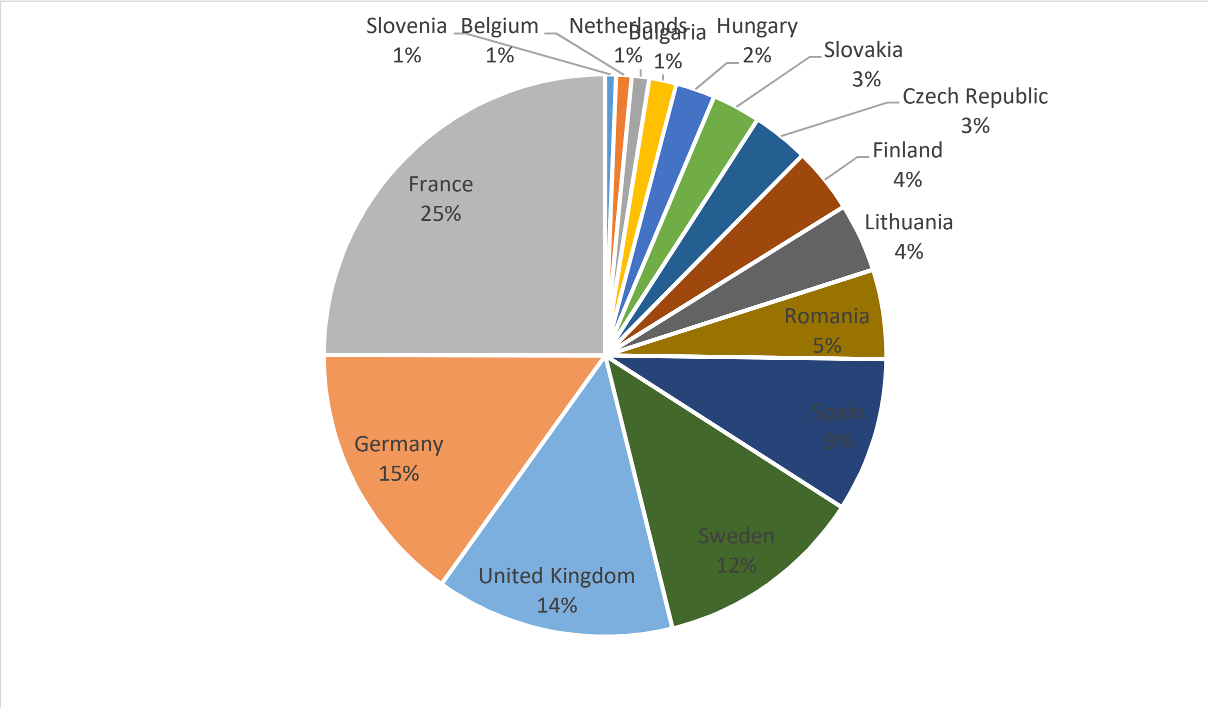

Figure 5: Reported SNF inventory in the European Union by country and share, as of 31.12.2016

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

Spent fuel is generally stored in the reactor cooling pools, or in an interim storage facility. The interim storage facility can either be dry storage, here SNF is stored in casks, or wet storage, where the fuel rods are stored in a pool. As illustrated in the chapter on risks below, wet storage is the most dangerous form of storage. Table 2 gives an overview of the amount of SNF still stored in different pools (inside of the reactor building or in a separated storage facility). In 2018, 80 percent or 45,629 t HM of the European SNF is still in wet storage. France and the U.K., the two countries that account for 40% of the current inventory have not transferred any SNF into dry storage. At least for the U.K, no data were given for dry storage, but a dry storage facility has been constructed at the Sizewell NPP. The UK report adds that the estimated total spent fuel arising from 40 years' operation at Sizewell B is 1,049 tons. EDF Energy's intention is to switch all the station's spent fuel from pools to dry storage by 2040. Only a few countries have transferred the majority of the spent fuel into dry storage. Particularly Hungary (17 percent) and Slovakia (10 percent) have the lowest rates of wet storage. Of course, none of these countries has yet a disposal solution installed for the amounts of SNF and the available storage capacity is currently being exhausted (e.g., the storage capacity for SNF is with around 93% in Finland nearly reached).

Country	SNF inventory [Mg HM]	Wet Storage [Mg HM]	Dry Storage [Mg HM]	Share of wet storage
France	13,990	13,990	0	100%
United Kingdom	7,700	7,700	0	100%

Sweden	6,758	6,758	0	100%
Finland	2,095	2,095	0	100%
Slovakia	1,559	1,559	0	100%
Netherlands	562	562	0	100%
Slovenia	350	350	0	100%
Bulgaria	875	788	87	90%
Spain	4,975	4,400	575	88%
Lithuania	2,210	1,417	793	64%
Belgium	501	237	263	47%
Romania	2,882	1,293	1,589	45%
Germany	8,485	3,609	4,876	43%
Czech Republic	1,828	654	1,174	36%
Hungary	1,261	216	1,045	17%
Total	**56,031**	**45,629**	**10,403**	**81%**

Table 2: Reported SNF inventory in Europe and amount of SNF in wet storage, as of 31.12.2016, as of,

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

3.3.2 Reprocessing Spent Fuel

In Europe reprocessing is still part of the waste management concept in some countries (i.e., France, Netherlands, Russia), while some countries have abandoned or stopped it (i.e., Belgium, Bulgaria, Germany, Hungary, Switzerland and most recently the U.K.). Others have never practiced it (i.e., Czech Republic, Finland, Lithuania, Romania, Slovakia, Slovenia, Sweden, Spain). While the majority of countries has abandoned reprocessing, especially due to economic reasons, the latest European country to show interest in reprocessing is Ukraine, where a contract with France's Orano (formerly Areva) "for assessing the feasibility of reprocessing services of spent fuel assemblies of Ukrainian VVER-1000 nuclear reactors in La Hague facility" was signed; the contract is part of Ukraine's effort to diversify its nuclear fuel cycle. In addition a spent fuel interim storage facility is constructed and the country is working with Westinghouse to use its fresh fuel (International Panel on Fissile Materials 2018).

With the exception of France, the U.K., and Russia most countries have to send their SNF abroad for reprocessing to either France, the U.K., or Russia, while the vitrified wastes (mostly HLW) are send back to the country of origin. With the closure of the THORP facility in 2018 (UK Government 2018), La Hague remains the last commercial reprocessing plant in Western Europe. The UK's latest report stated, after reprocessing has ceased, the THORP Receipt and Storage Pools would continue to store between 5,500 and 6,000 tons of fuel (United Kingdom 2017, 12). Central and Eastern European countries send their SNF mostly to the Russian Federation for reprocessing. Bulgaria, for example, had long term commercial contracts for SNF reprocessing services with Russia but all SNF transports stopped since 2014[6] but Bulgaria still holds the option open for future transportation of SNF for storage and reprocessing, if the economic conditions are favorable; the latest report does not include any indication on the amounts of wastes that have returned to Bulgaria (Republic of Bulgaria 2017). In Hungary, spent fuel from Paks (in total 273 t HM) was also transported back to the USSR and until 1998

[6] In the period between 2009 and 2014, 2,400 VVER-440 FA were transported to Russia.

to Russia for reprocessing. However, in the 1990's Russian wanted Hungary to take back the residual radioactive waste and other by-products created during reprocessing (NEA 2017). To cope with the waste, Hungary started with the construction of a centralized interim storage facility in 1993. With the abandonment of reprocessing Hungary has to store 1,261 t HM of SNF as well as 102 m^3 of HLW. Another example for a country that abandoned reprocessing is Germany: Until the end of June 2005, German utilities send their SNF to the UK or France for reprocessing; the separated plutonium was used for MOX fuels and fully reused in German LWRs. The German inventory lists the amounts of SNF that were reprocessed: around 42% or 6,343 Mg HM.[7]

Joining France, the Netherlands stick to reprocessing, too. Here the SNF policy is up to the operator (i.e. reprocessing or not) but reprocessing was done for all SNF in the past and the current operator—of the only operational NPP Borssele—has entered into reprocessing contracts with France for all SNF to be produced up to the end of the operating period (Kingdom of Netherlands 2017, 16).[8]

Table 3 gives an overview of the amounts of waste that stem from reprocessing. As mentioned above, there is no indication on the volumes present in Bulgaria. More than half of the HLW stems from France; together with the U.K. around 85 percent of the total European Member States HLW can be attributed to those two countries. The only two countries, that specify the amounts of ILW associated to reprocessing are France and Belgium.

Country	Active Reprocessing	HLW [m3]	ILW [m3]
France	Yes	3,650	46,300
United Kingdom	No	1,960	
Germany	No	577	
Belgium	No	285	3,132
Hungary	No	102	
Netherlands	Yes	91	
Bulgaria	No	n.a.	n.a.
Switzerland	No		
Russia	Yes		
Total		6,665	49,432

Table 3: HLW and ILW from reprocessing, as of 31.12.2016

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

[7] The report lists 6,670 Mg HM of SNF being removed form the core for either reprocessing (in La Hague, Sellafield, WAK, and Belgium) or permanently remaining abroad (Federal Republic of Germany 2018, 66).
[8] SNF from research reactors will not be reprocessed but directly transported to COVRA.

3.3.3 Volumes of SNF and HLW/ILW from Reprocessing

In order to get a grasp not only of the weight but also a rough estimate of the volumes of the stored spent fuel, one can apply the U.S. Department of Energy ratio of conversion from mass (t HM) to volume (m^3) for LWRs[9] as the majority of reactors can be attributed to the LWR technology. Again, this can only be seen as a rough estimate. In France, the volumes of ILW exceed the amounts of HLW and SNF stored; more than 40 percent of the total waste volumes from the management of SNF can be attributed to France. Together with Germany and France, the top three are responsible for 65 percent of the European Union SNF wastes.

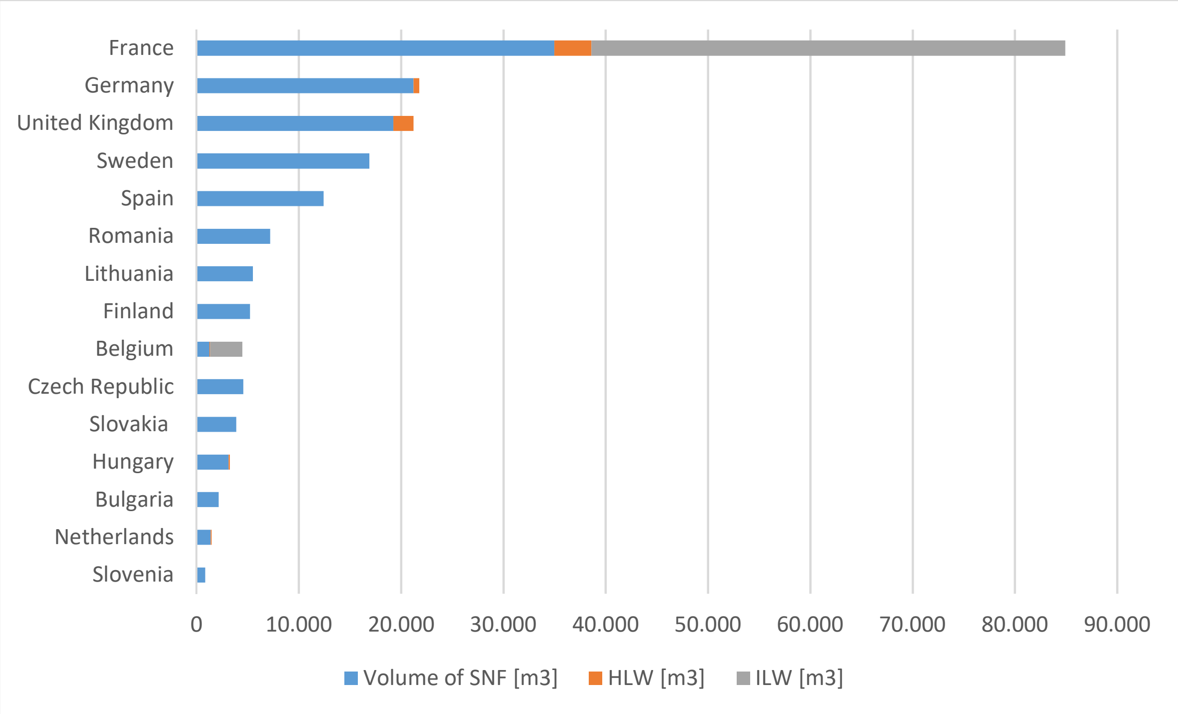

Figure 6: Cumulative volumes of waste incl. SNF,HLW, and ILW, as of 31.12.2016

Source: Own compilation.

3.4. Decommissioning Wastes

In 2018, only 19 NPPs have been decommissioned worldwide, only five of them have been in Europe and all in Germany (Schneider et al. 2018). Although, Germany has some decommissioning experience, the German report does not give exact amounts of wastes generated during decommissioning; only a rough estimate for the waste generation rate is given: 5,000 m^3 of conditioned decommissioning wastes per reactor. Although, it is stated in the report that this is based on progressive improvements and that “great efforts are undertaken to clear materials” (Federal Republic of Germany 2018, 86). On the other hand, the IAEA (2007) does not give estimates about the volume but about the weight of the decommissioning waste: a 1 GW_e LWR can be expected to generate 5,000-6,000 tonnes of LILW and 1,000 tonnes of LILW-LL and HLW (IAEA 2007b, 16). Although, all these estimates have to be seen critically as decommissioning of a 1 GW_e reactor is nearly non-existent worldwide - the five decommissioned German reactors were also small prototype and demonstration reactors. With 6,000 tonnes per GW_e as a representative average, the decommissioning of the European nuclear power

[9] The U.S. Department of Energy uses a ratio of 2.5 for LWRs for the conversion of SNF mass (MTHM) to volume (m^3) (U.S. Department of Energy 1997).

plants[10] would generate overall around 1,200,000 tonnes of LILW and nearly 200 tonnes of long-lived LILW and HLW. This excludes of course any new build reactors.

As it is the case with operational wastes, decommissioning wastes depend on various factors, e.g. the clearance levels of wastes, the decommissioning strategy (immediate dismantling or long-term enclosure), the operating time, or the reactor technology. The generated wastes in the initial stages of decommissioning have the same characteristics as operational wastes and can be characterized using the same approach; however, there is one main difference: the generated volumes are much higher and are generated in a shorter period of time (IAEA 2007a, 2).

In addition to the challenge of having to decommission the largest reactor fleets in Europe, the UK, France, and Russia face additional challenges with the legacy fleet consisting mainly of gas-cooled reactors (GCRs) in France and the still operational Soviet-style RBMK reactors in Russia and Chernobyl in Ukraine. These reactor cores were constructed of many thousand tonnes of graphite blocks and a typical UK Magnox reactor can contain about 3,000 tonnes of highly irradiated graphite classified as ILW with the need for shielded and probably deep disposal storage due to long-lived isotopes (Laraia 2012). In France, too, the major part of the low-level long-lived waste (LL-LLW) is going to be the graphite waste from the gas-cooled reactors, which is going to arise during the decommissioning of the GCRs. In addition, there is not even a theoretical disposal route for the graphite waste (Schneider et al. 2018, 144).

Although decommissioning works are ongoing in Europe (e.g. in the U.K., France, Sweden) actual numbers of volumes of decommissioning wastes are hard to find. In Spain, it is estimated that the dismantling of the Spain reactors will rise around 112,000 m^3 of LILW (NEA 2013, 3), i.e. 11,200 m^3 of LILW per reactor, this is double the amount of the German estimate. Decommissioning works at the José Cabrera and Vandellos NPP generated 185 m3 of “special waste”—which will be disposed of with HLW, mainly from cutting of the reactor vessel internals, now stored in four dry storage casks on site (Spain 2017, 129). Hungary estimates that decommissioning of the 4 Paks units will rise 26,700 m^3 of LILW (6,700 m^3 per reactor) as well as 70 m^3 of HLW (Hungary 2017, 34).

Applying a very conservative 7,000 m^3 generation rate of decommissioning waste to the European nuclear fleet (operational and shut down reactors) indicates that around 2,000,000 m^3 of LILW will arise, only through decommissioning. Figure 7 gives an overview of the estimated decommissioning wastes by country. France will have to dispose of at least 490,000 m3 of LILW, i.e. 25 percent of the total European decommissioning waste, followed by Russia (17 percent), the U.K. (16 percent), Germany (12 percent), and Ukraine (7 percent). These top five countries account for more than 75 percent of the entire European decommissioning wastes.

[10] 182 operational NPPs and 102 shut down or in LTO NPPs with ~197 GW_e of installed capacity (Schneider et al. 2018),

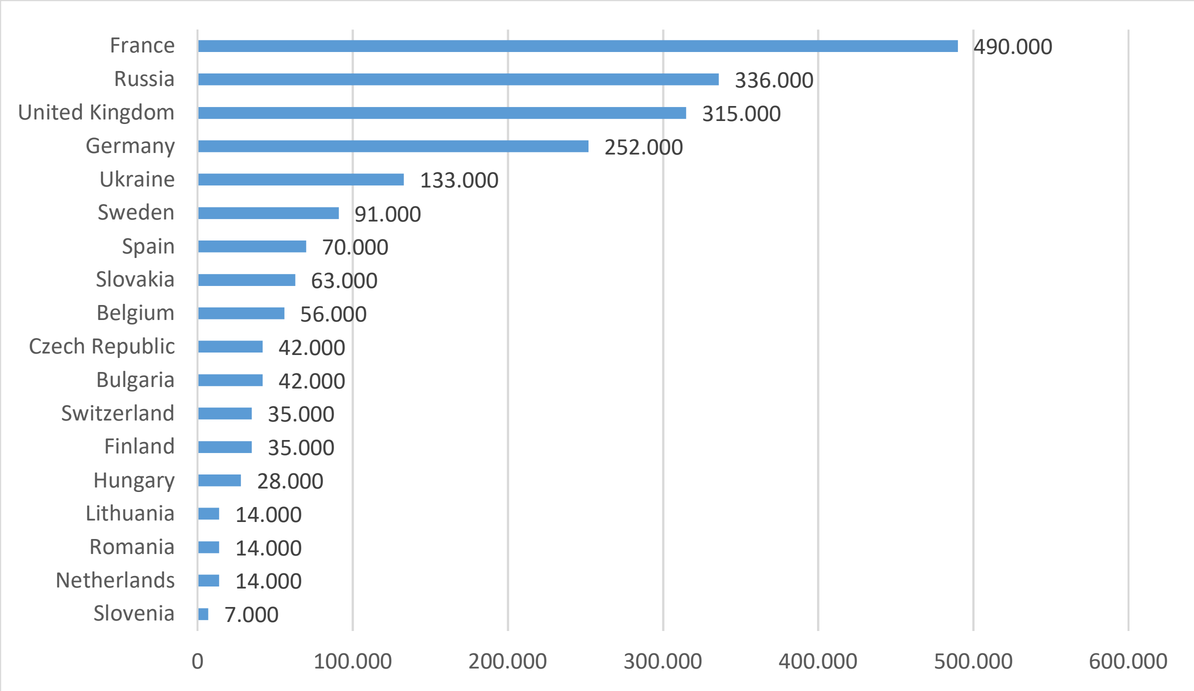

Figure 7: Estimated decommissioning waste volumes [in m^3] in Europe

Source: Own depiction.

3.5. Summary

Overall, the chapter concludes that a large amount of wastes has occurred in Europe, for which in most cases still no disposal facility exists. Even though the reported countries have to publish information on the amounts of wastes, comparison is difficult as the underlying waste classifications differ and in some cases the reported waste information cannot be used for volume estimation (e.g. Slovakia). In an order to attempt a comprehensive overview of the waste volumes, **Figure 8** adds together the reported LILW from operation, SNF and HLW / ILW from SNF management as well as the estimated decommissioning wastes. **Figure 9** does the same but excludes France and the U.K. for better readability. In the majority of the cases, decommissioning wastes will exceed the already large amounts of radioactive wastes present in Europe. In other words, the major part of the already ever increasing radioactive wastes lies still ahead of the nuclear countries. Uranium wastes are excluded as the majority of the uranium is imported and therefore creating large amounts of waste in the exporting countries and not in the European Union.

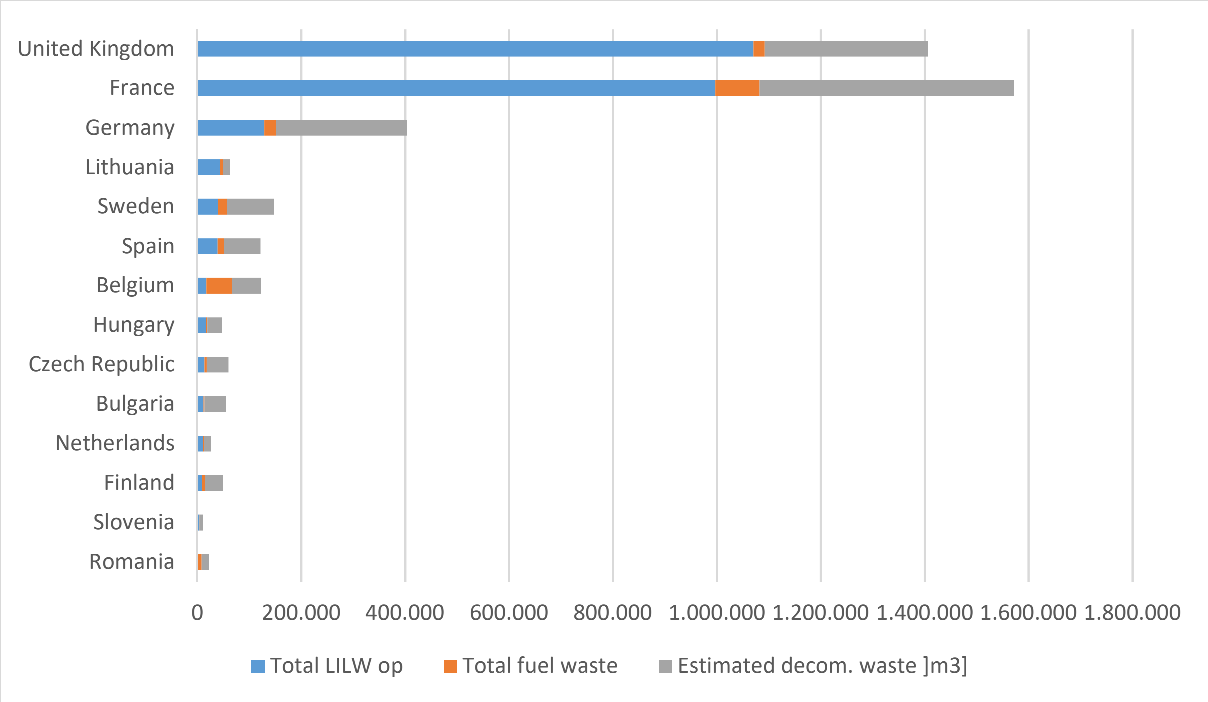

Figure 8: cumulative wastes from operation, SNF management, and decommissioning

Source: Own depiction.

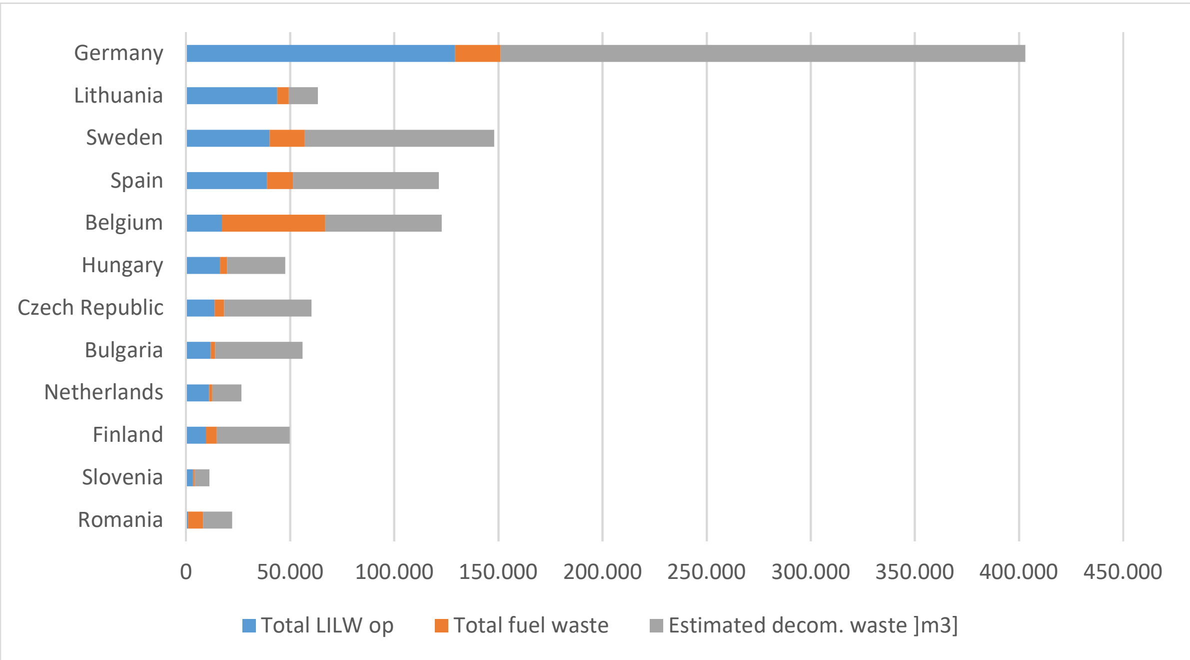

Figure 9: cumulative wastes from operation, SNF management, and decommissioning, without U.K and France

Source: Own depiction.

The European countries with the largest volumes of wastes are the United Kingdom and France, succeeded in most party by Germany. Adding up the present (in 2018) waste volumes (operation, SNF), both, France and the UK, have each nearly the tenfold of volumes than the Germany (on the 3d place).

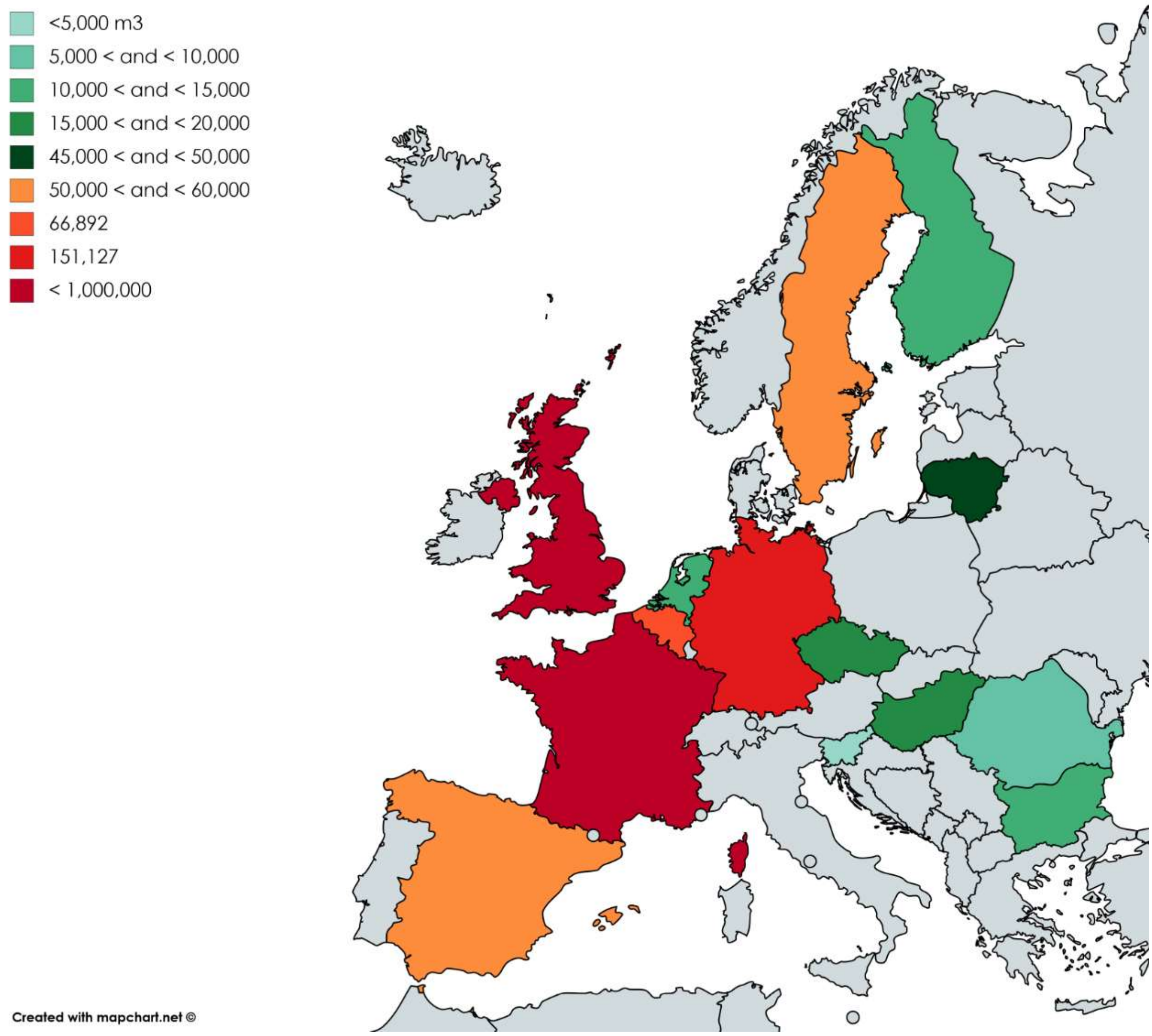

Figure 10: Overview of volumes of wastes in m3 stored in the European Union

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

Much more scrutiny should be paid to large amounts of SNF present in Europe, especially the SNF in wet storage – the most dangerous form of storage. In 2018, still around 80% of the SNF inventory is in wet storage. Transferring the SNF into dry storage should be safety priority. There seems to be a dire need for establishing a common reporting format as one can see in the “country overviews” the waste categories differ from country to country, even within the European Union making an exact and comprehensive comparison between the countries nearly impossible.

Overall, the chapter concludes that a large amount of wastes has occurred in Europe, for which in most cases still no disposal facility exists. Even though the reported countries have to publish information on the amounts of wastes, comparison is difficult as the underlying waste classifications differ and in some cases the reported waste information cannot be used for volume estimation. In an order to attempt a comprehensive overview of the waste volumes, the reported LILW from operation, SNF and HLW / ILW from SNF management as well as the estimated decommissioning wastes are added

together. In the majority of the cases, decommissioning wastes will exceed the already large amounts of radioactive wastes present in Europe. The European countries with the largest volumes of wastes are the United Kingdom and France, succeeded in most party by Germany. Adding up the present (in 2018) waste volumes (operation, SNF), both, France and the UK, have each nearly the tenfold of volumes than the Germany (on the 3d place).

Much more scrutiny should be paid to large amounts of SNF present in Europe, especially the SNF in wet storage – the most dangerous form of storage. In 2018, still around 80% of the SNF inventory is in wet storage. Transferring the SNF into dry storage should be safety priority. There seems to be a dire need for establishing a common reporting format as one can see in the "country overviews" the waste categories differ from country to country, even within the European Union making an exact and comprehensive comparison between the countries nearly impossible.

4. Risk issues

Nuclear waste has been described (Stothard, 2016) as "...the most destructive and indestructible waste in history." The US General Accounting Office (2012) has described used, i.e. spent, nuclear fuel as "... one of the most hazardous substances created by humans."

This chapter discusses the risks[11] to the environment and human health from radioactive waste facilities and from their releases to the environment. It will focus on higher activity wastes (see Annex B on IAEA's nuclear waste classifications) and highlight potential dangers and problems that have not been resolved. For example, although nuclear wastes pose both radiological and chemical risks, it will concentrate on the former, as these are more serious.

The chapter will also focus on the main risk drivers, ie those features, events and processes that pose the most serious dangers to people and the environment. Although risks arise from every step in the lengthy nuclear fuel chain, this chapter will concentrate on the hazards and risks of nuclear wastes arising from the following main steps:

- uranium mining, milling, enrichment, and fuel fabrication
- operation of nuclear power plants
- used (i.e. spent) fuel and reprocessed wastes, and
- reactor decommissioning

The chapter will briefly describe each step, its main hazards, and then attempt to quantify their risks using available data, if any. A major conclusion of this chapter is that much more data is required on the quantities of radioactive wastes, on their hazards and their risks. Such data collection and dissemination are primarily the responsibility of national governments. For example, Article 37 of the Euratom Treaty requires Member States to provide to the European Commission general data relating to any plan for the disposal of radioactive waste in their country. Clearly the higher the volumes of waste, the higher the risks. Similarly the higher the uncertainty on waste volumes/inventory data, the higher the uncertainty in risks.

4.1 Radiation Risks

Nuclear wastes can give off several types of radioactivity: alpha particles, beta particles, gamma rays and neutron radiation. Alpha particles are potentially extremely damaging to human health but can be stopped by thin barriers (e.g. paper). Beta particles are denser than alpha and can be stopped by denser materials such as water or aluminum. Gamma rays are much more difficult to stop than alpha or beta particles and it needs very dense materials like lead or concrete to absorb their energy and stop them. The potential harm to human health of exposure to radioactivity (radionuclides) varies according to the type of particle to which people are exposed. While alpha particles are most easily stopped, their effects are particularly damaging: they have a weighting factor of 20 compared to gamma rays (and X-rays) per unit of exposure.

Radiation from radioactive wastes, as from other sources, is carcinogenic, mutagenic and teratogenic[12]. Radiogenic cancer risks depend, inter alia, on the type of cancer, the tissues exposed, the dose, dose rate and type of radiation. The final risk to individuals will also depend on their gender, age, and time-since-exposure. Radiation is also increasingly implicated in a wide range of other

[11] "Risk" is defined here as the most likely consequence of a hazard, combined with the probability of exposure to it, i.e. a function of both hazard and exposure.
[12] Resulting in damage to embryos and fetuses.

diseases including cardiovascular diseases, strokes, eye cataracts and mental effects. Due to reasons of space, these effects are not discussed in this chapter.

According to the International Commission on Radiological Protection (ICRP[13]), an external whole-body radiation dose of one sievert (Sv) results in an approximately five percent risk of fatal cancer in adults (ICRP 2007). However, the ICRP's numerical estimate was reduced by half through its use of a dose and dose-rate effectiveness factor (DDREF[14]) of 2 for solid cancers. Since 2013, most international agencies have ceased using DDREFs, so the real risk of fatal cancer has increased to at least 10 percent per Sv. Unfortunately, the ICRP has not stopped using DDREFs (see Annex D). Thus, governments and the ICRP in terms of tightened radiation limits have not recognized the perceived increased risks of radiation.

4.2 Radionuclides in Radioactive Wastes

Radioactive wastes can contain a wide range of radionuclides[15]: most are highly radiotoxic[16] and many have extremely long half-lives[17]. Estimating their risks to workers and the public depends on their half-lives, the existence of decay progeny, their radioactive decay modes[18], the chemical compounds which contain the radioisotope, their solubility in water, their transport modes through the environment, their relative biological effectiveness[19], on their radiotoxicity (usually based on their specific activity[20]), and finally on their dose conversion factor[21]. Furthermore, as in most instances exposures will be internal rather than external, doses and risks will also depend on their uptake rates, metabolisms and excretion rates in humans (i.e. biological half-lives).

Unfortunately, no proper hazard classification scheme exists for radionuclides, unlike the schemes for chemicals and biocides, although calls have been made for such a scheme to be established for radioactive wastes (Kirchner 1990).

4.3 Risks from uranium mining, mine tailings, refinement, enrichment, and fuel fabrication

Uranium mining, mine tailings, refinement, enrichment, and fuel fabrication are collectively termed the front end of the nuclear fuel path, and health risks arise at each of these stages. Nuclear energy is derived from the fission of specific uranium nuclei. Uranium is a radioactive substance naturally existing in the Earth's crust. Uranium deposits are more concentrated in some areas of the world, where the ore is mined and processed. The resulting mining wastes and slurries are the first nuclear wastes. It is widely recognized that exposures to uranium and its progeny are responsible for a major fraction of the total health and environmental impact from the nuclear fuel cycle (IAEA, forthcoming).

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[13] A voluntary body with no official status. It acts as a trade association on radiation matters. Its recommendations are observed by many governments.

[14] DDREFs were formerly used to reduce risks derived from the Japanese bomb survivors to exposures to low dose and low dose rate radiation. Older cell and animal studies had indicated these were less harmful than exposures to higher doses at higher dose rates. More recent human studies have now shown the use of DDREFs is incorrect.

[15] A radionuclide (or radioisotope or nuclide) is an element whose atoms are unstable. When their nuclei disintegrate, they give off various forms of radiation.

[16] Radiotoxicity means the degree to which a radionuclide can damage an organism per Bq of the radionuclide

[17] Half-lives is the time it takes for half of the original amount present to decay to other atoms.

[18] The emission of alpha particles, beta particles and gamma rays.

[19] The ratio of damage from one type of radiation relative to another, given the same amount of absorbed energy.

[20] Specific activity of an element is its radioactivity (Bq) per gram.

[21] Which converts Becquerel to Sieverts.

Although the industry states that global uranium mining has decreased by 4 percent since 2013 (NEA/OECD 2016), the decline in global uranium mining has accelerated more recently. No uranium mining occurs in Europe at present but clean-ups continue at former mines in France, Germany, the Czech Republic and Romania.

4.3.1 Health risks from exposures to uranium

The health risks associated with exposures to uranium (including depleted uranium[22]) include kidney disease, respiratory disorders, DNA damage, endocrine disruption, cancers and neurological defects (UNIDIR 2008; ATSDR 2013; Wilson and Thorne 2015; Raymond-Whish et al 2007)). For example, Raymond-Whish et al (2007) have stated "uranium is an endocrine-disrupting chemical and populations exposed to environmental uranium should be followed for increased risk of fertility problems and reproductive cancers."

Animal and cell studies have indicated that uranium's health detriments are due to its affinity for DNA (Miller et al, 2002) and to the potential synergism between its chemical and radioactive properties. It is theorized, for example, that uranium's radiological and chemical effects might play tumor-initiating and tumor-promoting roles, respectively (Miller et al 2004).

Natural uranium comprises U-238 (99.27 percent by mass), U-235 (0.72 percent) and U-234[23] (0.0055 percent): this report will therefore focus on U-238. Uranium in ore is invariably accompanied by U-238's decay progeny, including thorium-234, protactinium-234m, protactinium-234, thorium-230, radium-226, radon-222, polonium-218, actinium-218, radon-218, lead-214, bismuth-214, polonium-214, thallium-210, lead-210, bismuth-210, polonium-210, thallium-206, and finally lead-206 which is stable. See Annex E for the decay chain of U-238.

Each of the above nuclides individually is estimated to be more dangerous than the parent U-238. Together these decay products in uranium ore contain about 14 times more radioactivity than the parent U-238.

The most problematic nuclide is radium-226 because its salts are mainly soluble, because it has a long half-life (1,760 years) and because it emits gamma rays. Another dangerous nuclide is radon-222 (half-life 3.8 days) as it is an odourless, colourless gas which means that it and its progeny, although invisible, are readily distributed in the environment.

Exposures to radon gas are considered to be the second leading cause of lung cancer worldwide, that is after tobacco smoking (Darby et al 2005; Pawel and Puskin 2004). The US Environmental Protection Agency (EPA) has estimated that indoor radon exposure causes or contributes to about 21,000 lung cancer deaths in the United States annually (Pawel and Puskin 2004).

Another unusually dangerous uranium decay product is polonium-210 (half-life 138 days) which was used in the 2006 death of the Russian dissident Alexander Litvinenko in London, UK. Polonium-210 is extremely radiotoxic: a few milligrams are enough to kill the average adult - e.g. it is much more toxic than hydrogen cyanide weight for weight (Sublette 2006).

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[22] This is depleted in U-235. DU is controversial and its use is banned in many countries. It continues to be used by military forces in other countries.

[23] U-234 is a decay product of U-238

Partly for these reasons, the ICRP (2010) estimated that a lifetime excess absolute risk (EAR)[24] of 5 × 10^{-4} per WLM[25] should be used as the risk coefficient for radon progeny induced lung cancer, doubling its previous estimate in Publication 65 (ICRP 1993). However several ICRP authors later added that if lung cancer rates among Euro-American males had been used instead of inappropriate ICRP reference rates (viz males and females and Euro-American and Asian populations), the risk actually increased to 7 × 10-4 per WLM (Tirmarche et al 2012). This means the estimated risk rates for most uranium mine workers have approximately trebled rather than doubled since 1993. This increase in perceived risk has not been reflected in tighter safety standards for uranium workers.

4.3.2 Uranium Mining

Although many uranium mines are now closed, the past history of uranium mining throughout the world remains bleak with many accidents and many reports of ill health among uranium miners. Older epidemiology studies indicated significant excesses of lung cancer (Grosche et al 2006; BEIR IV 1999) amongst uranium mining workers. Perhaps the best-documented example in Europe is the Wismut mine complex in Saxony and Thuringia in former East Germany. Between 1945 and 1990, the Soviet-run uranium mine complex employed about 30,000 workers often in poor working conditions. It continued to operate until 1996.

Kreuzer et al (2010) examined 58,987 Wismut miners employed for at least 6 months between 1946 and 1989 at these mines. By 2004, 3,016 deaths from lung cancer, 3,355 from extra-pulmonary cancers, 5,141 from heart diseases and 1,742 from cerebro-vascular diseases had occurred, a total of 13,254 deaths, i.e. 22.4% of the miners. The large majority of these deaths would have been due to occupational exposures. This was, and remains, an extremely high death rate – most likely unprecedented in modern occupational epidemiology studies. These high death rates are rarely, if ever, mentioned in industry publications on the benefits of nuclear power.

Kreuzer et al observed a statistically significant[26] increase in lung cancer risks with increasing radon exposure (ERR/WLM = 0.19 percent). Since one WLM is equivalent to ~ 5 mSv, this amounts to a fatal lung cancer risk of about 40 percent per Sv, ie about eight times higher than the ICRP's current estimated risk of 5 percent per Sv.

After reunification in 1990, the German Government commenced remediation of Wismut. By 2011, this was 80 percent complete and had cost €5.6 billion. By 2022, it is expected that rehabilitation will have cost more than €7 billion (Hoffman 2011).

Some uranium mines remain in sporadic operation throughout the world depending mainly on the market price for uranium. None operates in Europe. Therefore, health issues continue to arise especially in underground mines (WISE undated). In France, although all uranium mines have now closed, their remediations remain matters of public concern and local disputes.

4.3.3 Uranium Mine Tailings

After mining, milling and the removal of uranium from its ore, the residues are pumped to tailing piles or pools. Since the average uranium content in ore is typically about 0.1 percent to 0.15 percent,

[24] Cancer risks are expressed using either the Excess Relative Risk (ERR) model or the Excess Absolute Risk (EAR) model. ERR is the proportional increase in risk over the background rate (i.e. where people are not exposed). EAR is the additional risk above the background rate.
[25] One working level (WL) refers to the concentration of short-lived decay products of radon in equilibrium of 3,700 Bq/m^3 (100 pCi/L) in air. A working level month (WLM) is the exposure to one working level for 170 hours per month. I.e. a 40-hour workweek. It is conventionally assumed that 1 WLM = ~5 mSv.
[26] Statistically significant means, conventionally, there is a less than 5 percent probability the finding was due to chance.

virtually all ore winds up in the tailings. The result is very large amounts of tailings at uranium mines. Canadian mine companies, for example, have accumulated about 213 million tons[27] of uranium mine tailings (LLRWMO 2004) and 109 million tons of waste rock, as of the end of 2003.

In addition, in Canada, the process has generated about 400 million cubic meters of contaminated process water. Because of the large volumes of sulphuric acid used , high levels of heavy metals such as copper, zinc, nickel and lead are mobilized which are highly toxic to aquatic and terrestrial wildlife. Severe contamination of ground water constitutes a permanent risk.

Health Canada, a department of the Canadian Government, has stated "There is a serious possibility that the food chain can be contaminated unless appropriate mitigation is instituted. Fish, wildlife, vegetation, country foods, and drinking water are all at risk should spills or leakages occur. The need to manage the water from waste management areas is important, particularly if there are drinking water sources in the vicinity." (Health Canada 2008). However, leakages do occur frequently. In the Elliot Lake area in Ontario, for example, over thirty tailings dam failures have been reported (WISE undated).

Also in the US, the infamous Church Rock Uranium Mill spill in 1979 occurred in New Mexico, US, when the uranium mill tailings disposal pond breached its dam. Over 1,000 tons of radioactive mill waste and millions of gallons of mine effluent flowed into the Puerco River, and contaminants traveled downstream (Brugge et al 2007). Undisturbed ore contains all the radioactive daughters of uranium listed above in section 2.3 in secular equilibrium[28]. This means that uranium mill tailings contain all the progeny of the U-238 decay chain.

The summed radioactivity of these nuclides is approximately 80 percent of the radioactivity in the original ore, the exact percentage depending on how long the ore has been exposed to air. Tailings can also contain significant quantities of hazardous chemicals such as copper, zinc, nickel, lead, arsenic, molybdenum, and selenium depending upon the ore source and the reagents in the milling process.

Uranium tailings remain problematic because their radionuclides have multiple routes to man. Radon gas and the radioactive decay products of radon can be inhaled. Radioactive and toxic chemicals can be ingested with food and water, and external gamma radiation is emitted by the tailings. Contrary to popular belief, inhalation is the most important route as its collective doses are considerably larger than those from other paths.

The existence of tailings piles and tailing pools remains problematic because one of the decay products - thorium-230 (half-life 80,000 years) continues to generate the many nuclides in its decay chain for millennia. These accumulate under the coverings (assuming these exist) or they may penetrate or permeate them depending on the soil depths and the permeability of the various coverings currently in use.

Some problems have already been identified with tailings. For example, Pérez-Sánchez and Thorne (2014) have discovered that radioactive lead-210 (half-life 22.3 years) and polonium-210 (half-life 138 days) can reach surface soils on top of tailings in high concentrations via plant uptakes.

Few reports have quantified the risks from uranium mill tailings. In an older report, the US Environmental Protection Agency (EPA 1983a) estimated the lifetime excess lung cancer risk of residents living near a bare tailings pile of 80 hectares (0.8 km^2) at two cases per hundred residents.

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[27] Ton = 1,000 kilograms. Termed “metric ton (MT)” in the US.

[28] Secular equilibrium means that the Bq amount of a radionuclide remains constant because its production rate (e.g. due to decay of its parent) is equal to its decay rate.

Since radon gas spreads readily with wind and rain, people further away will also be exposed. Although the risks to these individuals are expected to be small, they cannot be neglected as radiation risks extend down to zero dose. As potentially large numbers of people may be exposed, their collective doses[29] and risks must be estimated (Fairlie and Sumner, 2000). For example, the US EPA (1983b) estimated that the then uranium tailings deposits existing in the United States would cause 500 lung cancer deaths per century, if no countermeasures were taken.

The health risks associated with uranium conversion and enrichment are mostly due to the inhalation and/or ingestion of uranium in its different chemical forms. In the U-235 enrichment process, uranium concentrate from milling (U_3O_8), which is termed yellowcake, is converted into uranium hexafluoride (UF_6), a highly volatile gas that is extremely chemically reactive and radiologically toxic. In addition, UF_6 gas immediately reacts with water vapor in air to form hydrofluoric acid (HF) which is even more reactive and highly toxic causing pulmonary irritation, oedema, and corrosion of the lining of lungs at low concentrations. It also causes seizures, and even death in people exposed to high concentrations.

4.4 Spent Nuclear Fuel

After nuclear fuel has undergone fission for three to four years, it is termed 'spent' and is placed in cooling pools. The industry's adjective spent is misleading as the fuel remains radioactive for hundreds of years and continues to emit large amounts of decay heat. For example, even after 10 years' cooling, radiation dose rates from unshielded used fuel canisters range from 1 to 100 Gy per hour depending on the fuel's burnup[30] rate: a dose of 6 Gy is usually considered lethal. Even with heavily-shielded dry store casks, surface dose rates range from 0.5 to 0.6 mSv per hour (Fairlie 1997). This means that workers working nearby could be exposed to up to 1 Sv per year – a dangerously high level.

The continued long-term use of fuel pools at most NPPs worldwide constitutes a major risk to the public and to the environment (Alvarez 2011). Used fuel pools must be constantly monitored, continually cooled to remove decay heat, and chemically adjusted to ensure correct pH values. If cooling were to fail for any reason, the pools would fully evaporate within a few days and the fuel cans could burst open and ignite as their zirconium cladding would react strongly with oxygen in air (von Hippel and Schoeppner 2016). The same would occur if the pond waters were emptied for any reason, e.g. breach of the walls of the tanks resulting from terrorist attack. These problems are exacerbated by the fact that the lengths of time used fuels stay in pools has been increasing and now routinely extend for several decades.

Spent nuclear fuel contains most of the radioactivity in the world's nuclear waste, and consists of fission and activation products. The major activation products are plutonium-239, plutonium-240, plutonium-241, plutonium-242 and tritium. A series of so-called 'minor' actinides are also formed: neptunium-237, curium-242, curium-244, americium-241, and americium-243.

In addition, approximately 700 fission products are formed in spent fuel: most are very short-lived. The main risk drivers include caesium-134, caesium-137, strontium-90, technecium-99 and cobalt-60 as these have longer half lives and emit powerful gamma rays. Tritium (H-3) is also formed as a tertiary fission product.

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[29] Collective dose is the sum of the doses to all individuals in a population. Conventionally it is calculated by multiplying the average dose by the population.

4.4.1 Risks of Spent Fuel in Pools

In 2014, the US NRC examined whether to require most used fuel currently held in US pools at NPPs to be moved into concrete dry casks and storage vaults. Such a move would reduce the likelihood and consequences of a spent fuel pool fire. It concluded that the projected benefits did not justify the around $4 billion cost of a wholesale transfer (NRC 2014).

However, Hippel and Schoeppner (2016) criticized the NRC report for seriously underestimating the risk and consequences of a spent fuel fire. These researchers (2017) then modelled the very serious effects of hypothetical radionuclide releases if an accident were to occur at US nuclear fuel storage sites. The research paper contained maps illustrating the radioactive plumes across large areas of northeastern United States. The lead author, Professor Frank von Hippel (Stone 2016), stated “We’re talking about trillion-dollar consequences.”

In most nuclear countries, increasing amounts of used fuel are being left in cooling pools for longer and longer periods. The continued existence of used nuclear fuel in pools is an increasingly serious issue which remains unresolved not just in the US but in all nuclear countries. This situation is considered highly unsafe due to the increased perception of risks from terrorist attacks.

The absence of robust proven technical solutions and the existence of political opposition to plans for nuclear waste facilities make this difficult situation even more problematic. This present situation is highly unsatisfactory and poses considerable challenges for all nuclear Governments and for future generations. As a first step, most environment groups state that no more used fuel should be created and that, ideally, NPPs throughout the world should be closed down.

In the meantime, it is widely accepted that spent nuclear fuel requires well-designed storage for long periods to minimize releases of the contained radioactivity to the environment. Safeguards are also required to ensure that neither plutonium nor highly enriched uranium is diverted to weapons use. According to Feiveson et al (2011) “There is general agreement that placing spent nuclear fuel in repositories hundreds of meters below the surface would be safer than indefinite storage of spent fuel on the surface”.

4.5 The Reprocessing of Used Nuclear Fuel

Two main means exist for managing used nuclear fuel - storage and reprocessing: this section discusses the latter method. In 1950s and 1960s during the Cold War, nuclear weapons countries constructed reprocessing plants for the purpose of extracting fissile Pu-239 for weapons purposes from used nuclear fuel.

Reprocessing involves the dissolution of used fuel in boiling concentrated nitric acid, and the physico-chemical separation of Pu and U nuclides from the dissolved fuel. It is a difficult, complex, expensive and dangerous process which results in hundreds of nuclear waste streams, very large releases of nuclide wastes to air and sea, and large radiation exposures to workers and to the public. Raised levels of childhood leukemias in nearby villages are linked to the proximities of reprocessing plants at Sellafield (Fairlie and Körblein 2015) and La Hague (Pobel and Viel 1997).

About 85 percent of current annual used fuel arisings worldwide are stored: in other words, about 15 percent is reprocessed. Reprocessing creates large quantities of highly active liquid (HAL) wastes which are heat-producing and extremely radioactive. As described below, these liquid wastes present severe problems for current waste management - at least in the UK. Originally, it was planned for liquid wastes to be glassified and stored in a more manageable solid form called vitrified waste. However, such processes have proved difficult in the UK and the US - and much of these wastes may remain in liquid

form for the immediate future. In addition to HAL wastes, reprocessing also results in the following waste streams (this list is not exhaustive):

- very large emissions to air of radionuclides
- very large discharges to sea of radionuclides
- separated plutonium-239 which is fissile and therefore a proliferation risk
- thousands of drums of separated reprocessed uranium for which no use exists at present
- hundreds of steel canisters containing vitrified wastes
- radioactive graphite from AGR fuel sleeves and decommissioned reactors
- concrete silos filled with the fuel claddings stripped from used fuel, and
- many other radioactive wastes, including sludges, resins, filters from the many physico-chemical processes involved in reprocessing

4.5.1 Fissile Materials

The original purpose of reprocessing was to obtain fissile Pu-239 for nuclear weapons, but fissile material has ceased to be a rationale for reprocessing, at least since the early 1990s. [31] Nowadays, separated Pu-239 presents formidable proliferation headaches for those countries, which persist with reprocessing, especially with the increased perceptions of terrorist attacks in recent years.

In 2007, the UK's prestigious Royal Society stated "the potential consequences of a major security breach or accident involving the UK's stockpile of separated plutonium are so severe that the Government should urgently develop and implement a strategy for its long term use or disposal" (The Royal Society 2007). These stocks amounted to 100 tons in 2007. By 2017, they had increased to 140 tons (DBEIS, 2017). In the intervening 10 years, successive UK Governments have failed to develop a policy for these fissile wastes and have failed to stop the reprocessing which creates them.

4.5.2 MOX Fuels

A later purported justification for reprocessing was the need to use the separated plutonium oxide in mixed oxide (MOX) nuclear fuel. However, MOX fuel has proved to be a failure for several reasons. For example, spent MOX fuel is not reprocessed in France and the UK as it is very radioactive when it exits reactors and results in high doses to nuclear workers - even to managers in distant offices because of used MOX's extremely penetrating gamma radiation. It usually has to be stored in pools for a minimum of 10 years rather than 5 years making MOX fuel very expensive to use.

4.5.3 Reprocessing – in conflict with IAEA Principles of Nuclear Waste Management

The collective doses to the world's population from the long-lived gaseous nuclides C-14, and I-129, and from medium-lived Kr-85 and H-3 (tritium) emitted at Sellafield and La Hague are very large. The global collective dose, truncated at 100,000 years, resulting from the discharges of the La Hague reprocessing facility alone has been calculated to be 3,600 person sieverts per year (Smith et al, 2005) resulting in 350 fatal cancers per year. Continuing discharges at this level for the remaining years of La Hague's operational life would cause over 3,000 additional cancer deaths globally, if the linear no-threshold theory of radiation is applied.

The International Atomic Energy Agency (IAEA 1995) has laid down nine principles of radioactive waste management. The fourth requires that future generations are protected to the same level as exists

[31] Moreover, in June 2017, the UN General Assembly agreed the Treaty on the Prohibition of Nuclear Weapons, a legally binding international agreement to comprehensively prohibit nuclear weapons, with the goal of their total elimination. 122 nations voted for the Treaty, 69 did not vote. For those nations party to it, the treaty prohibits the development, testing, production, stockpiling, stationing, transfer, use and threat of use of nuclear weapons, as well as assistance and encouragement to the prohibited activities.

today. In addition, more recently the IAEA has stated "The preferred strategy for the management of all radioactive waste is to contain it and isolate it from the accessible biosphere" (IAEA 2012). It is difficult to see how the above large releases of nuclear wastes from reprocessing plants and their corresponding large collective doses can be regarded as complying with either the letter or spirit of the IAEA's Principles.

4.6 Reactor Decommissioning

After about 30 to 40 years' operations, it is expected that most NPPs will be shut down, their fuels removed and their cooling systems and moderators drained. This process of defueling, deconstruction, and dismantling of nuclear power plant is called decommissioning. Worldwide 154 nuclear reactors were awaiting, or are in various stages of decommissioning. Another 19 had been fully decommissioned, mostly in the US (13) and Germany (5). The average duration of reactor decommissioning is around 19 years, in most cases longer than the construction and operational period of the reactor combined (WNSIR 2018).

The NPPs will then put in a state of 'cold' storage[32] for around five years to allow time for radioactive decays- primarily for cobalt-60 (half-life 5.3 years) – as it emits energetic gamma rays. High Co-60 concentrations limit the time that workers can stay near disused reactors. It is only after this initial period that decommissioning can commence. The two basic strategies are Immediate Dismantling (ID) and Long-Term Enclosure (LTE, sometimes called "Safe Storage"). In general, ID is preferable, as the skills and experiences of operating staff can be used, a clear line of responsibilities still exists, public interest is continuing, and the finance set aside is more likely to match the necessary work. LTE usually runs the risk of losing human competences, clear lines of responsibility, and public interest, thus dragging out decommissioning for decades.

4.6.1 Hazards of Decommissioned Reactors

"Fully decommissioned" usually means that the remaining reactor hulks are no longer under regulatory control and are classified as intermediate nuclear waste. However this does NOT mean that the reactor hulks are safe and without danger.[33] Disused nuclear reactor shells contain very large amounts of residual radioactivity rendering them potentially dangerous to the public - essentially forever. This is not widely known. The main nuclides include (in order of their initial amounts):

- H-3 (half-life = 12.7 years)
- Fe-55 (2.7 years)
- Co-60 (5.3 years)
- Ni- 63 (100 years)
- Ni-59 (76,000 years)
- C-14 (5,730 years)
- Nb-94 (20,000 years)

In the absence of nuclide data for EU reactors, this chapter contains data on the nuclide inventory of a small (60 MW) decommissioned Canadian research reactor at Whiteshell, Manitoba over a 1,000,000 year period. Disused EU reactors will show similar patterns but with much larger initial amounts of nuclides. Just to make it clear – this is the residual radioactivity in the reactor structure after the fuels,

[32] The industry adjective "cold" for this storage is incorrect, as the reactor structures remain hot in both radioactive and physical terms for many years.

[33] In the US, a few research reactors have been fully decommissioned and transported as hulks in special convoys to US DOE sites for storage, but no plans have been published as to what to do with these reactor shells.

coolants and moderators have been removed. Shutdown NPPs contain large amounts of radioactivity which will last for hundreds of millennia. These nuclides constitute Intermediate Level Wastes (See Annex B for definition) and will require to managed for very long time periods.

4.6.2 Continued Radionuclide Emissions from Decommissioned Reactors

High levels of radionuclide emissions are released not only from operating reactors but also from shutdown ones, especially gaseous emissions of H-3 and C-14. Nuclide emissions data in the UK Government's annual RIFE publication (SEPA, 2017) reveal that the Winfrith reactors which closed in 1995 still emitted 2 x 1012 Bq per year of tritium in 2016 more than 20 years later. Similar patterns are observed at the long-closed reactors at Trawsfynyedd, Dounreay, Chapelcross and all closed Magnox stations. In Canada, the small experimental reactors at Whiteshell and Rolphton which were closed over 30 years ago are still reported as emitting GBq/a quantities of tritium. It is surmised that during their operations high concentrations of tritium and C-14 are absorbed into the concrete and steel structures of the reactors and their containment structures. After the cessation of fission, these nuclides continue to seep out over decades-long timescales.

4.6.3 Decommissioning vs Operational exposures

It has been claimed that worker exposures from reactor decommissioning will be large and that decommissioning should be postponed for as long as possible. However, the European Commission (EC) has calculated that the dose reduction from the closure of a nuclear plant is considerably greater than the impact of its decommissioning. The EC estimated that the collective dose from atmospheric emissions during decommissioning of a nuclear facility in the EU in 2004 was about 2 person sieverts per year, compared to about 150 person sieverts annually from the operation of each nuclear facility in the EU (EC 2005). In other words, there is no health reason for postponing the closure of NPPs. The data above indicate that shutdown nuclear reactors remain hazardous for many years after their closure – from not only the reactor shells but also their continuing nuclide emissions. These dangers are neither widely known nor discussed. As a first step to dealing with these hazards, it is necessary to publish data on the nuclide inventories of disused reactors, and their annual emissions in Europe.

4.7 Summary

Nuclear wastes are dangerous for several reasons. First are the reported health impacts from routine waste emissions from nuclear facilities. Second are the very large global collective doses from nuclear reprocessing and third is the unsatisfactory and unsafe condition of much of the nuclear waste already created. High-level waste (HLW) in the form of spent nuclear fuel or vitrified waste from reprocessing contains more than 90% of the radioactivity in nuclear wastes. However, there is no fully operational High Level Waste repository in the world, and none is expected in the foreseeable future. This means that estimates of the impacts of HLW disposal remain speculative, but HLW still poses key questions of intergenerational liability and justice. The very long time frames involved - the half life of Pu-239 is over 24,000 years - remains the single most important factor distinguishing nuclear wastes from other kinds of wastes.

A main conclusion is that nuclear fuel reprocessing creates more accessible forms of highly dangerous radioactive wastes, proliferation problems, high exposures to workers and the public, and radioactive contamination of the air and seas. This is carried out to create a waste form – vitrified waste –, which is considered to be worse for final disposal in a repository than unreprocessed spent fuel. In addition, all at vast expense to taxpayers. In short, reprocessing is a counterproductive, expensive and dangerous waste practice. The good news is that it is about to stop, at least in the UK.

Another main conclusion is the sheer lack quantitative or even qualitative information on risks associated with nuclear wastes. Much of the data on waste risks is restricted to a few countries, or is

very old, or is patchy in coverage. Much needed information, for example on nuclide inventories in wastes, simply does not exist in many countries.

However, not just raw data is needed. In order to assess risks, as it is necessary to also have hazard rankings which tie observed health effects to exposures. However, no comprehensive hazard scheme exists for the radionuclides in nuclear waste in contrast to the hazard rankings for chemicals and biocides, for example.

Risks may be derived from epidemiological studies, but in the nuclear sphere these are often notable for their absence and/or poor quality. That is, they are often cheap and quick ecological studies as opposed to better case-control and cohort studies. In several instances, epidemiology studies, which are indicative of risks and should be followed up, are not pursued. Also in situations where small studies which suggest increased cancers for example but which are individually too small to give statistically significant results, the normal solution is to carry out meta-analyses. These combine smaller studies in order to give statistically significant results. With nuclear wastes, this often does not occur because it is useful for nuclear proponents to dismiss awkward results behind the smokescreen of lack of statistical significance.

But the situation is even worse than that. In order to assess risks, it is necessary to have accurate doses, but these are often not estimated in epidemiology studies. Even if they do exist they can often be unreliable due to the large uncertainties which surround them.

In sum, the situation with nuclear waste risks is highly unsatisfactory compared to, for example, chemical risks. Here uncertainties and information gaps are catered for by building in safety factors based on the Precautionary Principle. For example, observed chemical risks of carcinogenicity in rats or mice are usually multiplied by factors of 10 or even 100 when they are applied to humans.

5. Summary and conclusion

1. **The analysis reveals that European countries differ significantly in their practices on how to classify nuclear wastes. These differences signify a lack of coherency and transparency. They make an exact and comprehensive comparison between the countries nearly impossible.** Despite authoritative guidance from the International Atomic Energy Agency (IAEA) and a - largely unsuccessful - attempt by the EU to harmonize waste classification systems for its member states, there are substantial differences between European classification systems, with even more variety when considering non-EU countries. While countries agree on the category of high-level waste (HLW), distinguished by the need to manage decay heat, they sharply disagree on whether spent fuel (the source of high level waste) should even be classified as a waste. Several countries regard spent fuel as waste, to be disposed directly. Others, however, regard it – once reprocessing separates plutonium and uranium – as a resource. Another common feature in the HLW category is that there is as yet no available long-term management route for HLW, though there is official consensus that deep geological disposal is the best way forward. Below the HLW category there is no consensus about classification. The main differences are between those countries that draw a distinction between short-lived wastes either intermediate or low level, and those, which do not. Some systems are based on the origins of waste, some on potential or actual disposal sites, and yet others on activity and half-lives. This is necessarily a source of confusion. Under current conditions, comparing countries is difficult as the underlying waste classifications differ and in some cases the reported waste information cannot be used for volume estimation.
2. **The analysis shows that a large amount of nuclear wastes have occurred in Europe. The European countries with the largest volumes of wastes by far are the United Kingdom and France, succeeded by Germany.** Adding up the present (in 2018) waste volumes of operation and spent nuclear fuel, both, France and the UK, have each nearly the tenfold of volumes than 3rd place Germany. In most categories, future waste from decommissioning existing nuclear power plants will exceed the already large amounts of radioactive wastes present in Europe. However, there is no fully operational High Level Waste repository in the world, and none is expected in the foreseeable future.

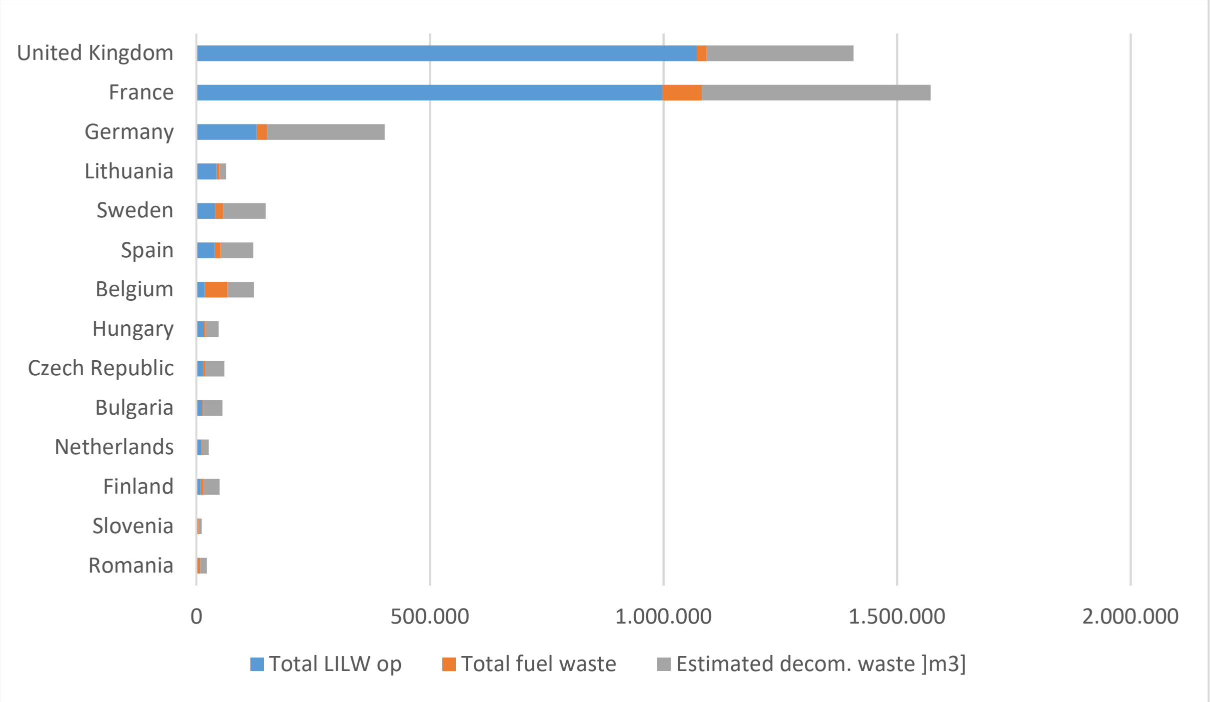

Figure 5.1: cumulative wastes from operation, SNF management, and decommissioning.

Source: Own depiction.

3. **Nuclear waste in its different forms is dangerous for various reasons.** First are the reported health impacts from routine waste emissions from nuclear facilities. Second are the very large global collective doses from nuclear reprocessing and third is the unsatisfactory and unsafe condition of much of the nuclear waste already created. The quantities and activity levels of the various categories of waste are inversely related. In other words the lower level wastes are produced in large volumes but contribute very little to the overall levels of radioactivity (and therefore potential harm). Conversely, high-level wastes are present in very small volumes but contribute the vast bulk of radioactivity. High-level waste (HLW) in the form of spent nuclear fuel (SNF) or vitrified waste from reprocessing contains more than 90% of the radioactivity in nuclear wastes. Spent nuclear fuel especially in wet storage, is extremely dangerous. Transferring the SNF into dry storage should be safety priority.
4. **The practice of nuclear fuel reprocessing creates more forms of highly dangerous radioactive wastes, proliferation problems, high exposures to workers and the public, and radioactive contamination of the air and seas**. This is carried out to create a waste form – vitrified waste –, which is considered to be worse for final disposal in a repository than unreprocessed spent fuel. In short, reprocessing is a counterproductive, expensive and dangerous waste practice.
5. **The analysis reveals an astonishing lack of quantitative and qualitative information on risks associated with nuclear wastes.** Much of the data on waste risks is restricted to a few countries, is very old, or is patchy in coverage. Much needed information, for example on nuclide inventories in wastes, simply does not exist in many countries. In order to assess risks, as it is necessary to also have hazard rankings which tie observed health effects to exposures. However, no comprehensive hazard scheme exists for the radionuclides in nuclear waste. In contrast, other industries like the chemistry sector provide a more robust risk assessment, such as hazard rankings for chemicals and biocides. Here uncertainties and information gaps are catered for by building in safety factors based on the Precautionary Principle. For example, observed chemical risks of carcinogenicity in rats or mice are usually multiplied by factors of 10 or even 100 when they are applied to humans. In sum, the situation with nuclear waste risks is highly unsatisfactory compared to, other risks and sectors.
6. **Finally, the very long time frames involved of tens of thousands of years remains the key factor distinguishing nuclear wastes from other kinds of wastes.** Even at a time if the radioactive waste will not be handled anymore but is finally disposed of, considerable hazards will emerge from this waste. Even the disposal in deep geological layers will not be a guarantee – due to the partially extremely long half-life periods of the substances – that the radionuclides will remain permanently isolated from the biosphere and thus from mankind.

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Annex I – Waste Tables

Reactor Technology	Annual volume (m^3) generated by 1 GWe of nuclear power	Number of reactors	Installed. Capacity [Gwe]	Total operational wastes [$m^{3/year}$]	Average age	Total generated operational wastes [m3]
AGR	650,0	14	7,7	5.005	35,4	177.177
BWR	500,0	9	7,9	3.950	36,5	144.175
PHWR	200,0	2	1,3	260	16,7	4.342
PWR	250,0	87	89,2	22.300	34,4	767.120
VVER	600,0	55	10,6	6.360	30,1	191.436
Total		**167**	**116,7**	**37.875**		**1.284.250**

Table 4: Estimate of present and future unconditioned volumes of operational LILW in Europe

Source: Own compilation based on IAEA (2007b).

Country	Operational NPPs	Average age of the fleet	waste from operational reactors [m^3]	Expected lifetime of NPPs [years]	Total operational LILW [m^3]
Belgium	7.0	38.3	16,086	50	21,000
Bulgaria	2.0	28.80	3,456	50	6,000
Croatia	0.5	36.7	1,101	50	1,500
Czech Republic	6.0	27	9,720	50	18,000
Finland	4.0	39.3	9,432	60	14,400
France	57.0	33.4	114,228	60	205,200
Germany	7.0	31.8	13,356	35	14,700
Hungary	4.0	33	7,920	50	12,000
Netherlands	1.0	45	2,700	50	3,000
Romania	2.0	16.5	1,980	50	6,000
Slovakia	4.0	26.3	6,312	50	12,000
Slovenia	0.5	36.7	1,101	50	1,500
Spain	7.0	33.4	14,028	50	21,000
Sweden	8.0	37.9	18,192	60	28,800
United Kingdom	15.0	34.3	30,870	40	36,000
Switzerland					
Ukraine					
Russia					
Total	**125**		**250,482**		**401,100**

Table 5: Estimate of present and future conditioned volumes of operational LILW in Europe

Source: Own depiction based on IAEA (2007b) and Schneider et al. (2018).

Country	Fuel assemblies (FA)	SNF [t HM]
Belgium	4,173	501[34]
Bulgaria	4,383	875
Czech Republic	11,619	1,828
Finland	13,887	2,095
France	-	13,990
Germany	-	8,485
Hungary	10,507	1,261[35]
Lithuania	19,7331	2,210[36]
Netherlands	-	562[37]
Romania	151,686[38]	2,882
Slovakia	13,102	1,559[39]
Slovenia	884	350
Spain	15,082	4975
Sweden	34,204	6,758
United Kingdom	-	7,700
Total	**-**	**56,031**

Table 6: Reported SNF inventory in Europe, as of 31.12.2016

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

[34] Data on fuel assemblies from 2011 Report. The eight was calculated assuming 120 kg per assembly.
[35] Weight was calculated assuming 120 kg per assembly.
[36] Weight was calculated assuming 112 kg per assembly.
[37] Data from 2009 Report.
[38] CANDU bundles.
[39] Weight was calculated assuming 119 kg per assembly.

Annex II - Country Overviews

BELGIUM

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim sorage (wet)	Reactor storage pool at Doel, Tihange	n.a.
	Interim storage (dry)	Doel	2,194 FA
	Interim sorage (wet)	Tihange	1,979 FA
	Reprocessed SNF		670 t HM at La Hague
HLW	Interim storage	Dessel, Mol	285 m^3 [40]
LILW	LILW	Dessel, Mol	17,302 m^3
	ILW from reprocessing		3,132 m^3
VLLW	No data on whereabouts and volume of the waste released		
Waste from Radium and Uranium production (Umicore)	Interim storage	3 storage facilities (UMTRAP, Bankloop, and "third").	95,000 m^3
Estimated future wastes	Category A: 70,500 m^3; Category B: 10,430 – 11,000 m^3; Category C: 600 m^3 – 4,500 m^3		

Table 7: Existing Waste Volumes in Belgium

Source: (Own depiction based on Kingdom of Belgium 2017, 34, 2012, 35).

* Data from 2012

BULGARIA

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Kozloduy	651 FA or 265 t HM
	Interim storage (dry)	Kozloduy	756 FA or 87 t HM
	Interim storage (wet)	Kozloduy	2,976 FA or 523 t HM
LILW Liquid	Interim storage	Reactor storage tanks	6,297 m^3*
LILW Solid	Interim storage	Reactor storage and interim storage	5,562 m^3*
Uranium-containing waste	tailings pond	Buhovo-1	$1.3*10^6$ m^3
	tailings pond	Buhovo-2	$4.5*10^6$ m^3

Table 8: Existing Waste Volumes in Bulgaria

Source: (Own depiction based on Republic of Bulgaria 2017, 18–22).

* The EC (2013) Report lists a LLW inventory of 23,000 m^3 and 10 m^3 of ILW.(European Commission 2013, 26)

CZECH REPUBLIC

[40] Belgium has reprocessed 672 tHM.

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Dukovany, Temelin	3,134 FA or 654 tHM
	Interim storage (dry)	ISFSF and SFSF at Dukovany, SFSF at Temelin	8,485 FA or 1,174 tHM
LILW Liquid	Interim storage	Reactor storage tanks	1,487 m^3
LILW Solid	Interim storage	Reactor storage and storage facility	707.5 m^3
	Dispsoed waste	Near-Surface repository Dukovany	11,520 m^3[41]
VLLW	No data on whereabouts and volume of the waste released		
U-holding waste	Tips + slurry settling facility	Straz, Dolni Rozinka (in recultivation)	n.a.

Table 9: Existing Waste Volumes in the Czech Republic

Source: (Own depiction based on Czech Republic 2017, 139–43).

FINLAND

Nuclear waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (wet)	Separate storage facility at Loviisa	5,167 FA or 626 t HM
	Interim storage (wet)	Separate storage facility at Olkiluoto	8,720 FA or 1,469 t HM
LILW	Interim storage	Loviisa	1,660 m^3
	Interim storage	Olkiluoto	310 m^3
	Near-Surface repository	Loviisa	1,886 m^3
	Near-Surface repository	Olkiluoto	5,681 m^3
VLLW	Interim storage	Olkiluoto	n.a.
	Dump site	Olkiluoto	n.a.
U-holding waste	Tips + slurry settling facility	Eno Askola	no data

Table 10: Existing Waste Volumes in Finland

Source: (Own depiction based on Finland 2017, 31–33).

FRANCE

Nuclear waste	Type of storage	Storage site	Volume stored

[4141] In addition, around 8,700 m^3 of instiutional waste has been disposed.

SNF	Reactor storage pool	Nuclear power plant sites	4,221 tHM
	4 storage pools	La Hague	9,681 tHM
	Storage pool	Creys-Malville	88 tHM
HLW	Interim storage	La Hague, Marcoule, CEA sites	3,650 m^3 [42]
ILW long-lived from SNF treatment	Interim storage	NPP sites, La Hague, Marcoule, CEA sites, research centers, Bouches-du-Rhone	46,300 m^3
LLW long-lived	Interim storage	NPP sites, La Hague, Marcoule, CEA sites, research centers, Le Bouchet	87,200 m^3
Tritium-holding waste	Interim storage	Côte D'Or	5,500 m^3
LILW short lived	Interim storage	NPP sites, conditioning plants, Marcoule, research centers, uranium plants	67,000 m^3
	Disposed waste	Shut down above-ground repository CSM	527,000 m^3
	Disposed waste	Operational above-ground repository (CSA)	316,000 m^3
Waste without classification		Site not named	1,800 m^3 [42]
VLLW	Interim storage	Conditioning plants	154,000 m^3
	Disposed waste	Operational above-ground repository CIRES	360,000 m^3
U-holding waste	Tips + slurry settling facility		50 million tonnes
disused radioactive sources			1,700,000 m^3
Estimated future wastes	HLW: 12,000 m^3; ILW-LL: 72,000 m^3; LLW-LL: 190,000 m^3; LILW-SL: 2,000,000 m^3; VLLW: 2,300,000 m^3 [42]		

Table 11: Existing Waste Volumes in France

Source: (Own depiction based on République Francaise 2017).

GERMANY

[42] Data from (ANDRA 2018).

Waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (dry)	Storage facilities at NPP sites	4,201 t HM
	Interim storage (dry)	ZLN, Ahaus, Gorleben	675 t HM
	Interim stroage (wet)	Reactor storage pool at NPP sites	3,609 t HM
	SNF send to reprocessing	851 t HM shipped to the UK; 5,393 t HM shipped to France; 14 t HM shipped to Belgium; and 85 t HM reprocessed at Karlsruhe	6,343 t HM
	SNF exported without return	283 tHM of VVER fuel returned to Russia, 17 tHM shipped to Sweden (CLAB), and 27 tHM of VVER fuel to be reused at PAKS in Hungary	327 tHM
HLW	Interim storage	NPP sites, ZLN, Land collecting facilites, centralized storage facilities	577 m^3
LILW	Reactor storage	NPP sites	14,631 m^3 and 12,308 tonnes
	Interim storage	Unterweser	1,422 m^3 and 1,106 tonnes
	Interim storage (dry)	Gorleben	6,979 m^3
	Interim storage (dry)	Mitterteich	8,200 m^3
	Interim storage	ZLN Greifswald	6,830 m^3
	Interim storage	Stade	4,403 m^3
	Interim storage	Research facilities	61,965 m^3 [43]
	Interim storage	Land collecting facilities	1,108 m^3
	Interim storage (dry)	Ahaus	1,633 m^3
	Interim storage	GNS and other storage facilities, Daher Nuclear Technologies, Nuclear Industry	13,160 m^3 and 211 tonnes
	Shut down geological repository	Asse II	47,000 m^3
	Shut down geological repository	Morsleben	37,131 m^3
VLLW	No data on whereabouts and volume of the waste released		
U-holding waste	Tips + slurry settling facility	Wismut (in recultivation)	46.5 million tonnes of heaps and 4.7 million m^3 of tailings

Forecasts	
Decommissioning waste generation rate	5,000 m^3 of LILW per reactor
Conditioned operational waste generation rate	45 m^3 of LILW per year, per reactor
Estimated total HLW waste	~ 27,000 m^3
SNF	20,400 m^3 or 10,173 Mg HM

structural parts and sleeves from SNF dispsosal	3,400 m^3
vitrified waste and from reprocessing	1,440 m^3
SNF from THTR	1,340 m^3
Waste packages with structural parts of SNF	3,400 m^3

Table 12: Existing Waste Volumes in Germany

Source: (Own depiction based on Federal Republic of Germany 2018).

HUNGARY

[43] Additional 7,376 tHM of raw and pretreated wastes.

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool atPaks	1,800 FA
	Interim storage (dry)	SFISF at Paks	8,707 FA
	SNF send to reprocessing	Send to Russia	2,331 FA or 273 t HM
HLW	Interim storage	Paks	102 m^3
LILW liquid	Interim storage	Reactor storage tanks at Paks	8,131 m^3
LILW Solid	Interim storage	Reactor storage facility at Paks	1,835 m^3
	Interim storage	Near-surface repository RWTDF	225 m^3
	Disposed waste	Near-surface repository RWTDF	4,900 m^3
	Interim storage	Near-surface repository NRWR	430 m3
	Disposed waste	Near-surface repository NRWR	876 m3
VLLW	No data on whereabouts and volume of the waste released		
U-holding waste	Tips + slurry settling facility	in recultivation	10 million m^3 of waste rock pils and 3.4 million m^3 of heap leaching piles
SNF	Estimated future waste		17,717 FA or 2,101 t HM
HLW	Generation rate of 3-5 m^3 per year		150 – 250 m^3 (50 years lifetime)
HLW	From decommissioning		300 m^3
LILW liquid	Estimated future wastes		12,980 m^3
LILW (conditioned)	From decommissioning		26,710 m^3[44]
LILW solid (conditioned)	From operation		Additional 2,890 m^3
LILW (conditioned)	Inventory of wastes planned to be disposed of at National Radioactive Waste Repository (NRWR)		15,889 m^3

Table 13: Existing and future Waste Volumes in Hungary

Source: (Own depiction based on Hungary 2017)

[44] 9,147 1.8 m^3 containers and 2,846 3.6 m^3 containers.

LITHUANIA

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim Storage (wet)	Reactor storage pool at Ignalina	12,653 FA or 1,417 t HM
	Interim storage (dry)	Ignalina	7,078 FA or 793 t HM
LILW liquid (and processed)	Interim storage	Ignalina	16,934 m^3
LILW Solid	Interim storage	Different storage sites at Ignalina	26,900 m^3
VLLW	Disposed waste	Landfill disposal facility	no data
Long-lived waste	To be diposed of in a geological facility	SNF 2,394 tHM; graphite: 3,834 tHM; operational and decommissioning waste: 5,035 tonnes; spent sealed sources: 128 m^3	

Table 14: Existing and future Waste Volumes in Lithuania

Source: (Own depiction based on Republic of Lithuania 2017)

NETHERLANDS

Nuclear waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Borsele	562 tHM[45]
HLW	Interim storage	Borsele	91 m^3
LILW	Interim storage	Borsele	11,109 m^3
NORM-wastes[46]	Interim storage	Borsele	20,622 m^3
VLLW	No data on whereabouts and volume of the waste released		
Depleted uranium-oxide	Long-term interim storage	Borsele	1,845 m3 [47]

Table 15: Existing and future Waste Volumes in the Netherlands

[45] Data from 2009 report.

[46] "*Depleted uranium as a special case of NORM Depleted uranium originating from the uranium enrichment facility of URENCO is also categorized as NORM. The tails that remain after the enrichment process are not considered as waste as long as they are available for re-enrichment. If URENCO decides that re-enrichment is not economically feasible, the tails are converted to solid uranium oxide in France and stored at COVRA. The uranium oxide is stored in standardized 3.5 m3 containers (DV-70) in a custom-built modular storage building. One storage module with a storage capacity of 650 containers became operational in 2004, two more in 2008 and with the construction of modules 4, 5 and 6 in 2011 the depleted uranium storage building (VOG) was completed. In 2017 a second depleted uranium storage building (VOG-2) became operational. VOG-2 has three storage modules, with each module having a capacity of 2,193 containers.*" (Kingdom of Netherlands 2017, 34–35)

[47] Data from 2009 report.

Source: (Own depiction based on Kingdom of Netherlands 2017).

ROMANIA

Nuclear waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Cernavoda	67,686 CANDU fuel bundles or 1,293 t HM
	Interim storage (dry)	Cernavoda	84,000 CANDU fuel bundles or 1,589 t HM
LILW short-lived	Interim storage	Reactor storage site at Cernavoda	912.125 m^3
LILW long-lived	Reactor storage site	Cernavoda	70 m^3
	Interim storage	Nuclear fuel plant Pitesti	25 m^3 [48]
Uranium Mining and Milling waste	Tips + slurry settling facility	CNU – Feldioara	2,692,800 m^3 of tailings
	Storage of low activity waste	CNU – Feldioara	25,605 m^3
	Tips + slurry settling facility	CNU – Suceava	767,590 m^3
	Tips + slurry settling facility	CNU – Stei (Bihor)	4,257,962 m^3
	Tips + slurry settling facility	CNU – Oravita (Banat)	2,057,000 m^3

Table 16: Existing Waste Volumes in Romania

Source: (depiction based on Romania 2017).

RUSSIA

SLOVAKIA

Nuclear waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Bohunice; Mochovce	1,336 FA
	Interim storage (wet)	Interim storage pool at Bohunice	11,766 FA
HLW	Reactor storage facility	Bohunice	213 cells*
LILW long-lived	Interim storage	no information	50 m^3 [49]

[48] In addition at the nuclear research institutes: LILW-SL 275 m3, LILW-LL 5.5 m^3, VLLW 437 m^3, and HLW 0.12 m^3. Romania operates the National Repository for Low and Intermediate Level Waste (DNDR), where 2,189 m^3 of waste from the "non fuel cycle" radioactive waste was disposed of.

[49] Data from 2004 Report.

LILW liquid	Reactor storage tanks	Bohunice V-1, V-2, A-1	5,087 m3
	Reactor storage tanks	Mochovce	2,003 m3
LILW solid	Reactor storage facility	Bohunice V-1, V-2, A-1	5,712 m3 + 389 pcs
	Reactor storage facility	Mochovce	449 m3
	Deposit of contaminated soil	Bohunice A-1	6,819 m3
	Above-ground repository	near Mochovce	4,800 m3**
VLLW	Storage facility	no information	4,000 m3

Table 17: Existing Waste Volumes in Slovakia

Source: Own depiction based on (Slovak Republic 2014).

* the information available does not allow any classification of volumes
*** from 2004
** this is the waste generated through nppps an treated in the conditioning plant at Bohunice before final disposing. The information available does not show whether or not any ohter waste from npps are finall deposited at Mochovce

SWITZERLAND

SLOVENIA

Nuclear waste	Type of storage	Storage site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at Krsko	884 FA or 350 t HM
LILW	Interim storage	In the decontamination building at reactor site Krsko	2,271 m^3
	Interim storage	In the Solid Radwaste Storage Facility at reactor site Krsko	1,044 m^3
	Interim storage	Central Storage Facility at Brinje	93 m^3
U-holding waste	Waste dump of uranium mine	Zirovski	1.9 million tonnes or 1.2 million m^3
	Deposit for residue from uranium ore processing	Zirovski	730,450 tonnes or 415,543 m^3

Table 18: Existing Waste Volumes in Slovenia

Source: own compilation based on Slovenia (2017).

SPAIN

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim storage (wet)	Reactor storage pools	13,681 FA or 4,400 t HM
	Interim storage (dry)	Storage facilities at NPP sites	1,401 FA or 575 t HM
Special Waste (treated as HLW)	Interim storage	Storage facilities at Vandellos and José Cabrera sites (from decommissioning)	185 m^3
LILW[50]	Interim storage	Storage facilities at NPP sites	5,748 m^3
	Interim storage	Near-surface repository El Cabril in Córdoba	1,000 m^3
	Disposed waste	Near-surface repository El Cabril in Córdoba	32,198 m^3
VLLW[51]	Interim storage	Storage facilities at NPP sites	3,964 m^3
	Interim storage	Near-surface repository El Cabril in Córdoba	3,912 m^3
	Disposed waste	Near-surface repository El Cabril in Córdoba	10,087 m^3
U-holding waste(Data from Neumann 2010, 79)	Mines + tips + slurry settling facilities (Salamance)	in recultivation	80.3 million t
	Mines + tips + slurry settling facilities (Badajoz)	shut-down and monitored	6.6 million t
	Mines + tips + slurry settling facilities (Jaen)	shut-down and monitored	1.2 million t

Table 19: Existing Waste Volumes in Spain

Source: own compilation based on Spain (2017).

SWEDEN

[50] In addition: 86 m^3 LILW at Juzbado fuel element factory; 2 m^3 LILW at CIEMAT research centre.

[51] In addition: 269 m^3 VLLW at Juzbado fuel element factory; 2,875 m^3 VLLW at CIEMAT research centre.

Nuclear waste	Type of storage	Storage site	Volume stored
SNF[52]	Interim storage (wet)	Reactor storage pools at NPP sites	2,387 FA or 492 t HM
	Interim storage (wet)	Central near-surface interim storage pool at Oskarshamn (CLAB)	31,817 FA or 6,266 t HM
LILW	Interim storage	Interim storage facility for LILW AM at the Studsvik site	2,301 m^3 [53]
LILW short-lived	Diposed waste	Near-surface repository at Forsmark	37,931 m^3
VLLW	Dump site	Shallow landfill sites at the NPP sites	27,841 m^3

Table 20: Existing Waste Volumes in Sweden

Source: own compilation based on Sweden (2017).

UKRAINE

UNITED KINGDOM

Nuclear waste	Type of storage	Storage Site	Volume stored
SNF	Interim storage (wet)	Reactor storage pool at NPP sites	3,549 t HM
	Interim storage (wet)	Sellafield	4,151 t HM
HLW	Interim storage	Sellafield	1,960 m^3
ILW	Interim storage	Sellafield, Aldermaston, Dounreay, Harwell, NPP sites	99,000 m^3
LLW	Interim storage	Sellafield, Capenhurst, Dounreay	30,100 m^3
	Disposed waste	Closed (in 2005) near-surface repository at Dounreay	33,600 m^3 [54]
	Disposed waste	New near-surface repository at Dounreay	3,130 m^3

[52] In addition: SNF from research reactors in a reactor storage pool (0.04 t HM).

[53] The waste includes mostly waste from research, the industry, or hospitals but also incinerated waste from nuclear power plants, decommissioning waste from old nuclear facilities, and waste treatment of steam generators from Ringhals.

[54] Data from (Neumann 2010, 56).

	Disposed waste	Near-surface repository LLWR at Drigg	905,000 m^3 [55]
VLLW	Interim storage		935 m^3
	Dump sites		no data

Table 21: Existing Waste Volumes in the United Kingdom

Source: own compilation based on United Kingdom (2017).

[55] Data from (Neumann 2010, 56).