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Assessing the Scale of the Radioactive Waste Management Problem: A Review of European Union and International Reporting

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Summary **— Information on the management of radioactive waste (RW), including inventory, can be obtained from several sources, such as the International Atomic Energy Agency (IAEA) and the European Commission. The IAEA is collecting voluntary national profiles through the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The European Commission is requiring reports from Member States in accordance with Council Directive 2011/70/Euratom, which establishes a framework for the safe and responsible management of spent fuel and radioactive waste. The findings from these reports are published by the IAEA and EC every three years and provide comparable information on RW policies, frameworks, and programs, with a significant focus on waste and spent fuel inventories and associated practices and technologies. This paper reviews the latest available reports from the EC and the IAEA, focusing on the RW inventory and disposal status. The paper presents some findings on the overall situation in the European Union (EU) and the comparison of inventories between EU Member States, as well as a comparison with the reporting from the IAEA regarding the global situation. The presentation of the radioactive waste and spent fuel inventories is normalized per person and land area, with the intention of improving understanding of the scale of the RW management problem. The relative scale of the problem is also demonstrated by comparison with hazardous waste inventories. There is a total of 264,000 tons of spent fuel worldwide, equivalent to concentration of 2 g/km² or 0.04 g/capita. The total amount of all categories of radioactive waste is 37.6 million m³, equivalent to 290 l/km² or 5 l/capita. The majority of RW (92%) is very low or low level, and 81% has already been disposed of. In comparison, ten times more hazardous waste is produced worldwide each year (~50 kg/capita/year). These numbers indicate that the amounts of RW are relatively small. The status reports, with a high percentage of RW disposed of, show that RW is routinely manageable, including the management of high-level RW. This is also demonstrated by the fact that Finland is soon to open a permanent disposal site, with several other countries following suit.**

Keywords **— radioactive waste inventory, waste directive, hazardous waste, disposal**

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I. Introduction

Information about the status of radioactive waste management (RWM), including inventory information, can be obtained from various sources such as the International Atomic Energy Agency (IAEA) and the European Commission (EC). The IAEA is compiling voluntary national profiles under the Joint Convention on the Safety of Spent Fuel Management and the Safety of RWM. The EC, on the other hand, is requesting reports from Member States every three years in accordance with the Council Directive 2011/70/Euratom (Waste Directive), which establishes a framework for the responsible and safe management of spent fuel and radioactive waste. Both sources provide comparable status and trends related to radioactive waste policies, frameworks, and programs, with a particular focus on waste and spent fuel inventories and the development of practices and technologies.

This paper reviews the latest available reports from the IAEA and the EC, with a focus on the inventory of radioactive waste and spent fuel and the status of its disposal. The paper presents some findings related to the overall situation in the world and compares the inventory between EU Member States. The presentation of radioactive waste and spent fuel inventories is normalized per capita and per land area, which is not commonly done and aims to improve the understanding of the scale of the RWM problem. Finally, the relative scale of the RWM problem is compared with the inventories of hazardous waste at the global and European Union levels.

The main objective of the Waste Directive is to ensure a high level of safety in the long-term management of radioactive waste and to improve transparency and public participation in the European Union (EU). Member States are legally obligated to report on the implementation of the waste directive and the status of their inventory every three years, which makes it easier to compare national programs and reports as they follow a common format and requirements. The EC reviews the submissions and reports its findings to the Council and the European Parliament. The waste directive covers all sources of radioactivity, including nuclear spent fuel and related inventories. The latest available report from the EC was published in 2019, covering all Member States including the UK.

The IAEA reporting has similar goals, with the main difference being that reporting by Member States is voluntary. The aim is to publish updates every three years, in sync with the reporting cycle of the Joint Convention. The latest report, from 2022, covers the status as of the end of 2016 (the same as for the EU) and covers 83 Contracting Parties, including the EU. This reporting is subject to a peer-review process.

This paper does not cover uncertainties related to inventory and information about radioactive waste generated by military activities. These uncertainties are mainly related to waste categorization and differences during conditioning. Both the IAEA and EC present inventories using the IAEA GSG-1 classification (Very Low Level Waste, Low Level Waste, Intermediate Level Waste, and High Level Waste). Spent fuel is treated separately as some countries are using or considering reprocessing. Naturally occurring radioactive materials (NORM[1]) and disused sealed radioactive sources are not covered in this paper as not all countries consider them separately and they present relatively less significant amounts of radioactivity.

The paper is organized as follows: after the introduction, the next section provides highlights on the status of radioactive waste and spent fuel, including inventories. Section 3 presents normalized inventories of radioactive waste, spent fuel, and hazardous waste. The final section provides some conclusions.

II. Radioactive waste and Spent Fuel Management Status Overview

This paper focuses specifically on the inventories of spent fuel (SF) and radioactive waste (RW). For a more comprehensive understanding of the SF and RW status, the information presented here should be supplemented by the International Atomic Energy Agency (IAEA) status and trend report on SF and RW management [1]. This includes data on the European Union and the specific findings related to the EU have been taken from the European Commission reporting under the Waste Directive and EC staff working documents [2], [3], and [4].

In the first section, the frameworks for SF and RW management are briefly discussed. The second section provides an overview of the established practices and technologies used in the management of SF and RW.

A. Frameworks for spent fuel and radioactive waste management

According to the EU Waste Directive, the Joint Convention, and the IAEA, the primary responsibility for the safety of SF and RW rests with the license holder. However, the state has an obligation to ensure that necessary programs and regulations are in place to manage SF and RW safely. The government establishes a legal and regulatory framework that outlines the roles and responsibilities of all involved parties, including the public.

In most EU and OECD/NEA countries, a clear separation between the regulatory body and the ministry responsible for energy or industry is preferred. National policies should address the responsibilities, financial arrangements, preferred management options (including decommissioning), and public involvement. National strategies are developed to implement these policies by waste management organizations (WMO), which could be state-run or privately-owned (usually by the utility company). The regulatory body or responsible ministry usually approves the strategy.

In most countries with operating nuclear power plants, a dedicated financial system is in place to manage the cost of SF and RW management, including decommissioning. These costs are generally a small contribution to the overall cost of energy production.

Final waste disposal is expected to take place in the country where it is generated, as outlined by the Joint Convention and the Waste Directive. The export and import of SF and RW are prohibited in many states, with exceptions for reprocessing and treatment services. Disused sealed radioactive sources (DSRS) are typically returned to the suppliers.

Early involvement of stakeholders throughout the life cycle of a nuclear facility, including storage and final disposal, is critical. Waste facilities will be in operation for many years and pose potential hazards for hundreds to thousands of years, depending on the category of RW. The Waste Directive provides for necessary public information and participation, and various international conventions also cover stakeholders' involvement, such as the Aarhus Convention (access to information, decision-making participation, and environmental justice) and the Espoo Convention (transboundary environmental impact).

B. Developed practices and technologies

Radioactive waste management encompasses the entire life cycle, including facility operation, RW generation, characterization, treatment, storage, and final disposal. The management of RW involves reduction from primary, secondary, and recycling sources. The potential for recycling and reuse is limited on a national level. Final disposal is defined as the intentional placement with passive engineered and natural isolation, without the intention of retrieval (although this may vary in some countries). The management of SF and RW is highly regulated and internationally accepted safe technical solutions have been developed.

SF is mostly kept in wet or dry storage until a final solution is found, which may be reprocessing or direct disposal. Currently, only a few countries[2], such as France, Japan, and Russia, are reprocessing SF. Some countries utilize SF reprocessing services, while China operates a pilot reprocessing plant. Reprocessing of SF results in high-level waste (HLW), typically in the form of a vitrified material, which is ready for final disposal. In both cases, final disposal is planned in a similar manner as for long-lived intermediate-level waste (ILW) and HLW, in deep geological repositories. In some countries, there may be plans for possible retrieval.

New storage facilities for SF are being built farther from reactors and may even be located outside of the plant boundaries. For longer storage, different types of dry solutions are becoming increasingly popular. The canisters of HLW after reprocessing are stored in air-cooled vaults or casks, similar to those used for SF.

Finland is the first country to reach the stage of operating license submission for a deep geological repository (DGR) located 400 meters or deeper and is expected to start accepting SF in a few years. Several other countries, including France, the UK, Canada, and Germany, are in various licensing stages for their DGRs. Sweden has recently issued a construction license for their geologic disposal repository. There are approximately 20 underground research laboratories in use for SF and HLW DGRs, such as HADES in Belgium, KURT in South Korea, and Krasnoyarsk in Russia.

Intermediate-level waste (ILW) often contains large amounts of long-lived radionuclides and requires shielding during handling and deeper disposal locations. Treatment and conditioning processes, such as separation, volume reduction, and stabilization prior to packaging, are carried out to ensure safety. This may include drying, evaporation, high compaction, melting, and cementing. ILW is packaged in concrete containers with steel reinforcement, steel boxes, or drums and can be stored for up to 100 years before final disposal. Final disposal is typically done in DGRs located about 100 meters below the surface and is considered safe. The Wa-

[1] E.g.: extraction of fossil fuels and rare earths, phosphate sector, titanium production, geothermal energy.

[2] The commercial capacity for SF reprocessing was (at the end of 2016) 44000 t HM/a. However, in the meantime UK THORP and Magnox reprocessing capacities (900 and 1500 t HM/a) are permanently closed.

Zdenko Šimić, Assessing the Scale of the Radioactive Waste Management Problem: A Review of European Union and International Reporting, Journal of Energy, vol. 72 Number 1 (2023), 8–13
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ste Isolation Pilot Plant in the USA is a licensed disposal facility for ILW. Some countries, such as Germany, Switzerland, and France, are planning to dispose of ILW together with HLW in DGRs.

Low-level waste (LLW) shares many similarities with ILW regarding treatment and storage. Incineration is an important part of the compacting process for LLW. Low-level waste is typically stored for a longer period before final disposal is available. The main difference between LLW and ILW is that LLW has a lower radioactivity level and a much larger volume. Most LLW radionuclides have a half-life of less than 30 years. Many countries have been disposing of large volumes of LLW in near-surface repositories or in caverns below ground level for several decades. Engineered barriers prevent water infiltration and intrusion, and surveillance is planned for a few hundred years. Some countries are considering disposing of LLW at deeper locations or collocating it with ILW, which could be more complex due to the higher volume and additional requirements.

Very low-level waste (VLLW) is mainly generated from decommissioning activities and consists of concrete, soil, and rubble. Only a few countries, such as France, Japan, Lithuania, Spain, and Sweden, treat VLLW separately. Little processing is done for VLLW, except for packaging and potential separation for clearance. A simpler shelter or temporary cover is sufficient for VLLW storage. Final disposal is usually done in shallow trenches or above-ground designs with a concrete slab. Some countries dispose of VLLW together with other LLW or non-nuclear hazard waste.

There has been significant progress in the disposal of low-level and very low-level waste, with disposed volumes much higher than stored volumes. The most important considerations for these types of waste are long-term knowledge management and preservation, transparency, and stakeholder involvement. Active international cooperation, research, and development are crucial for ensuring technology and experience progress in this field.

C. SF and RW Inventories

The classification of RW, as previously mentioned, varies in different countries, and the calculation of the total amount, for the EU and world, requires conversion based on the information provided by the countries or with some assumptions. This adds some degree of uncertainty. The global data presented in this report is at an improved level of aggregation compared to the previous IAEA status report. More detailed information can be found at the country level in references [1] to [4].

Table 1 provides the cumulative amounts of SF in wet and dry storage across various regions of the world, including reprocessing, in terms of 1000 metric tons of heavy metals (HM). Table 2 presents the cumulative amounts of RW for all categories in 1000 cubic meters. The table also provides the share of RW that has already been disposed of. Values for EU Member States are presented both in the European region and separately.

Due to the much smaller quantities, SF from research reactors is not presented in detail. Similarly, DSRSs are also not covered here because some countries classify them together with their respective RW categories. In many countries, DSRSs are the primary or only type of RW.

Globally, there are 390000 metric tons of HM of SF (43% of which is in the EU), including reprocessed material (which makes up one third of the total, and 68% of which is in the EU).

In terms of volume, globally there is only 0.13% of HLW, 7.7% of ILW, while the majority is LLW (53%) and VLLW (39%). These numbers are similar in the EU, with a larger difference in the share between the two largest categories: 0.2%, 9.7%, 72%, and 18%, respectively. When expressed by radioactivity, VLLW and LLW together make up less than 2% worldwide.

Globally, more than 80% of RW, by volume, has already been disposed of (more than 70% in the EU). However, only a small fraction of ILW (5% globally, and 4% in the EU) and none of the HLW has been disposed of as of the end of 2016. As previously mentioned, the first disposal of SF will start in Finland after the operating license is issued (the regulatory review started in May 2022 and may take several years).

Table I

Reported Spent Fuel from Nuclear Power Plants (1000 t HM, end of 2016), [1]

REGION, SF 1000 t HM	**Wet storage**	**Dry storage**	**Reprocessed**	**Total**
Africa	1.0	0.05	-	**1.0**
Americas	83.5	52.5	0.6	**136.5**
Asia	35.5	6.5	8.5	**51.0**
Europe	63.5	20.5	117.5	**201.5**
Oceania	1 t	-	1 t	**1 t**
WORLD TOTAL	**183.5**	**80.0**	**127.0**	**390.0**
EU Member States	42.0	11.0	113.0	**166.0**
HM - Heavy Metal				

Table II

Reported Solid Radioactive Waste (1000 m3, end of 2016), [1]

REGION	**VL LW**		**L LW**		**I LW**		**H LW**
1000 m³	Total	Dis-posed	Total	Dis-posed	Total	Dis-posed	Total
Africa	14	0%	39	36%	1	0%	0
Americas	13350	83%	15695	98%	176	53%	6
Asia	351	0.2%	316	21%	69	0%	6
Europe	614	60%	3892	77%	2626	2%	17
Oceania	432	100%	28	86%	0	-	0
WORLD TOTAL	**14761**	**80%**	**19970**	**93%**	**2872**	**5%**	**29**
EU Member States	614	60%	2493	84%	333	4%	6
VL - Very Low; L - Low; I - Intermediate; H - High; LW - Level Waste							

The volume of RW continues to rise with the operation of nuclear power plants, at a rate of approximately 2% per year. However, comparison with previous years is challenging due to changes in RW classification reporting. The amount of RW generated also depends on the technologies used for processing, storage, and disposal. With the increasing number of reactors set to be decommissioned, larger quantities of LLLW and LLW are expected to be generated in the future. Currently, fewer than 20 reactors have been decommissioned globally. At the end of 2016, 123 reactors were in the decommissioning process, and a significant number of reactors are expected to be decommissioned in the future as more than 140 operating reactors are over 40 years old (which is typically the extended operating time for reactors).

As of the end of 2016, there were 448 reactors in operation (with a combined capacity of 391 GWe) in 30 countries. In the EU, 14 Member States have nuclear power plants in operation (119 GWe in 126 reactors), and along with Italy and Lithuania (which have terminated their nuclear programs), they account for 99.7% of the RW volume. Three reactors have been decommissioned and 90 have been shut down. There are 82 research reactors (including those in decommissioning) in the 19 Member States.

III. Radioactive and nonradioactive hazardous waste concentration comparison

A comparison between radioactive waste (RW) and nonradioactive hazardous waste (HW) such as toxic, corrosive, biological, explosive, and flammable, can improve both the management and perception of related problems. This comparison could include regulations, trade, toxicity, presence in the environment, and longevity. This paper begins this complex comparison by focusing on the quantities of RW and HW. The comparison is done by calculating concentration as the amount of waste per capita and per land area ([7, 8, 9, 10]). The calculations are first made for RW using global and regional data and country data (for EU Member States). Then, global HW and EU MS data are used to calculate the concentrations per capita.

Globally, approximately 400 million tons of HW are produced annually (the total amount of all waste is estimated to be about 20 times larger) [5]. The trade of HW between countries is growing and is estimated to be about 40 million tons per year.

Figures 1 and 2 show the quantities of RW and HW per land area (left side) and per capita (right side) for different regions in the world. It is evident that so far, the accumulated quantities of RW are equal to about 10 liters per person and less than 1 m^3 per square kilometer of land area (for example, 6.7 l/capita and 0.78 m^3/km^2 for the EU). Similarly, the accumulated quantities of SF are equivalent to a fraction of a gram per person and several grams per square kilometer of land area (for example, 0.1 g/capita and 12 g/km^2 for the EU).

Figures 3 and 4 show the density in the EU MSs for RW and SF respectively (per land area on the left side and per capita on the right side). The graph for SF data shows MSs with a nuclear program, including two former nuclear MSs (Italy and Lithuania) and Croatia (which shares a nuclear power plant with Slovenia and will soon take over half of the RW from the 40 years of operation of the NPP Krško). The graph for RW shows all MSs.

The accumulated amounts of SF are less than 30 grams per person and less than 25 kilograms per square kilometer of land area (excluding non-nuclear MSs). Correspondingly, the accumulated amounts of RW are less than 5 liters per person and much less than 2 m^3 per square kilometer of land area (for example, 0.3 l/capita and 0.02 m^3/km^2 for Croatia).

To illustrate the small concentration of RW it might be interesting to estimate the quantities of SF and RW per person in a hypothetical scenario where only nuclear power is used to generate electricity for a person's lifetime. This evaluation is dependent on many assumptions, and for an approximate estimate, it seems reasonable to judge based on the data presented for EU MSs that the burden would be approximately 1 kg of SF and about 30 liters of RW (including about 3 l of ILW and half a liter of HLW) per capita.

Based on the global amounts of nonradioactive hazardous waste, it can be estimated that approximately 50 kilograms are produced per person annually. Detailed data for world regions are not easily available. Country statistics about HW for the EU MSs are available. Figure 5 shows the quantities of HW treated in EU MSs in kilograms per person every year. About half of the MSs have quantities comparable to the global average. However, eight MSs have quantities greater than 200 kg/capita/year.

These data show that the amounts of HW generated per person every year are about 10 times larger than the cumulative amounts of RW generated since the beginning of the use of nuclear power (during more than 50 years).

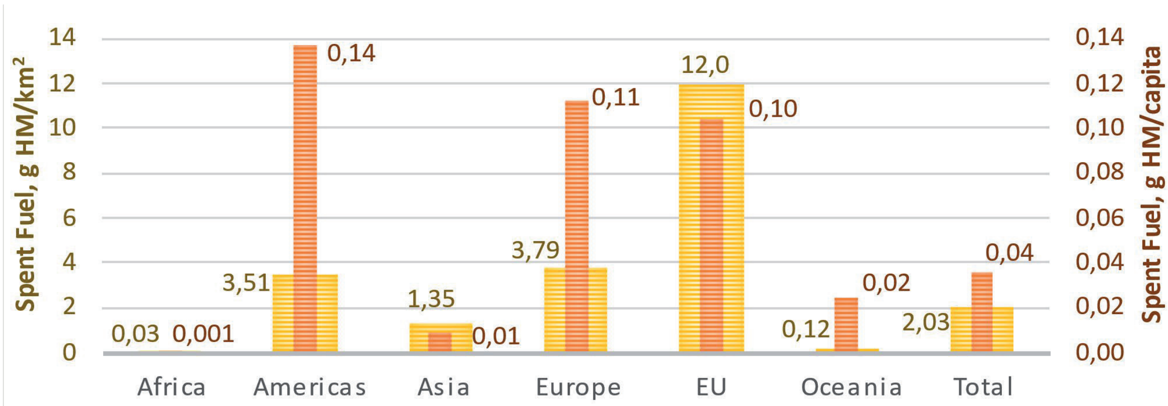

Fig. 1. Accumulated Concentration of Spent Fuel for World Regions: kg HM/capita and g HM/km², [1] (HM – Heavy Metal)

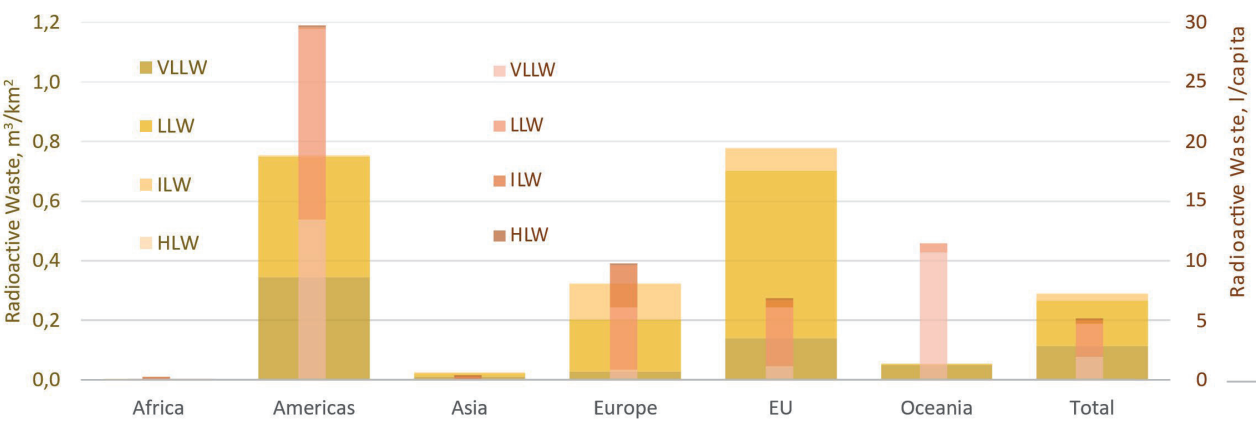

Fig. 2. Accumulated Radioactive Waste Concentration for World Regions: m³/km² (wide bars) and l/capita (narrow bars), [1]

Zdenko Šimić, Assessing the Scale of the Radioactive Waste Management Problem: A Review of European Union and International Reporting, Journal of Energy, vol. 72 Number 1 (2023), 8–13
https://doi.org/10.37798/2023721424

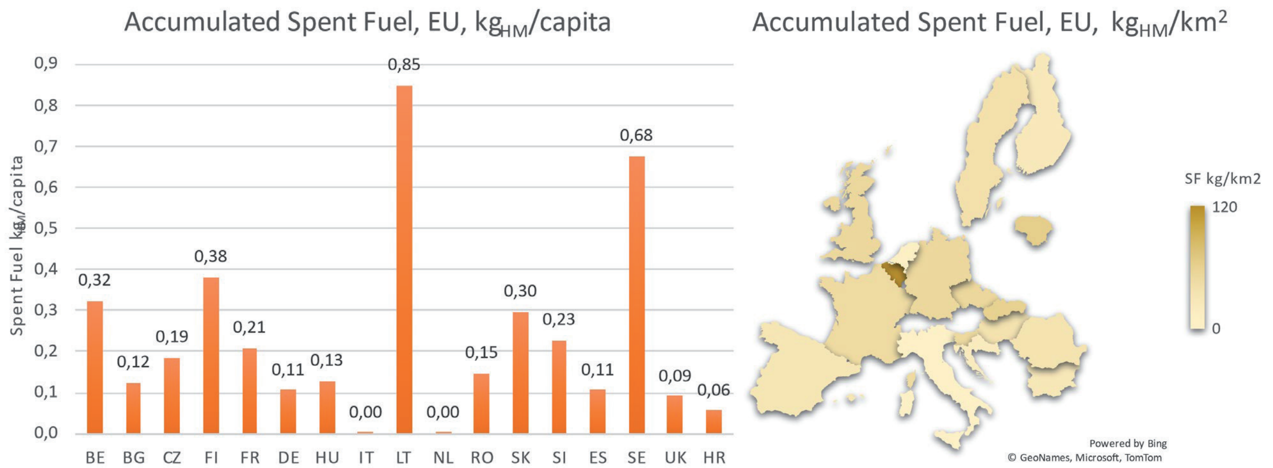

Fig. 3. Accumulated Spent Fuel Concentration in the European Union: kg HM/capita (MSs with nuclear program) and kg HM/km² (HM – Heavy Metal. Data for HR include share from the SI.), [4]

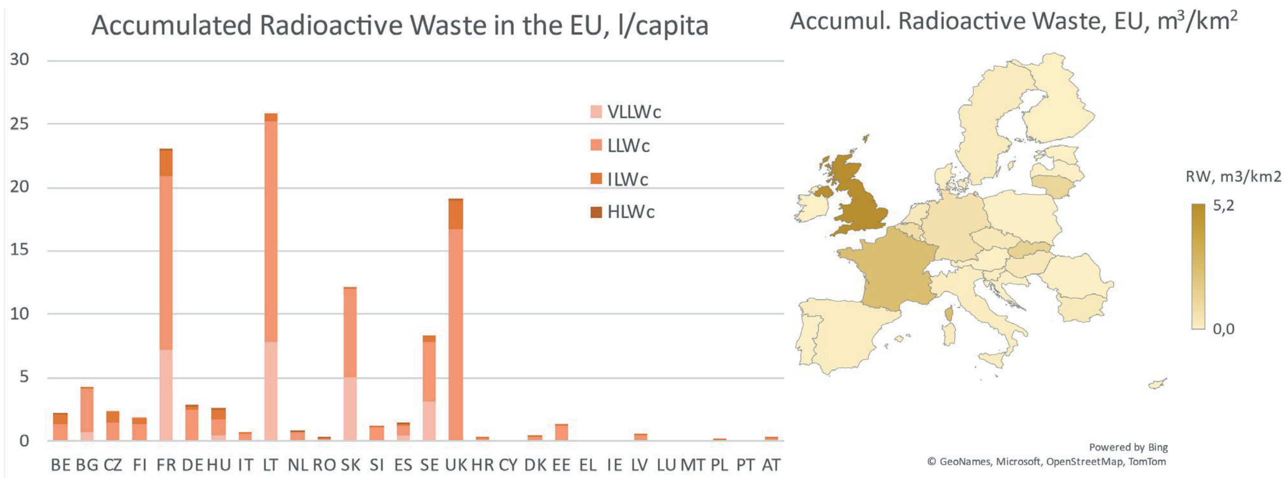

Fig. 4. Accumulated Radioactive Waste Concentration in the European Union: l/capita and m³/km² (All MSs. Data for HR include share from the SI.), [4]

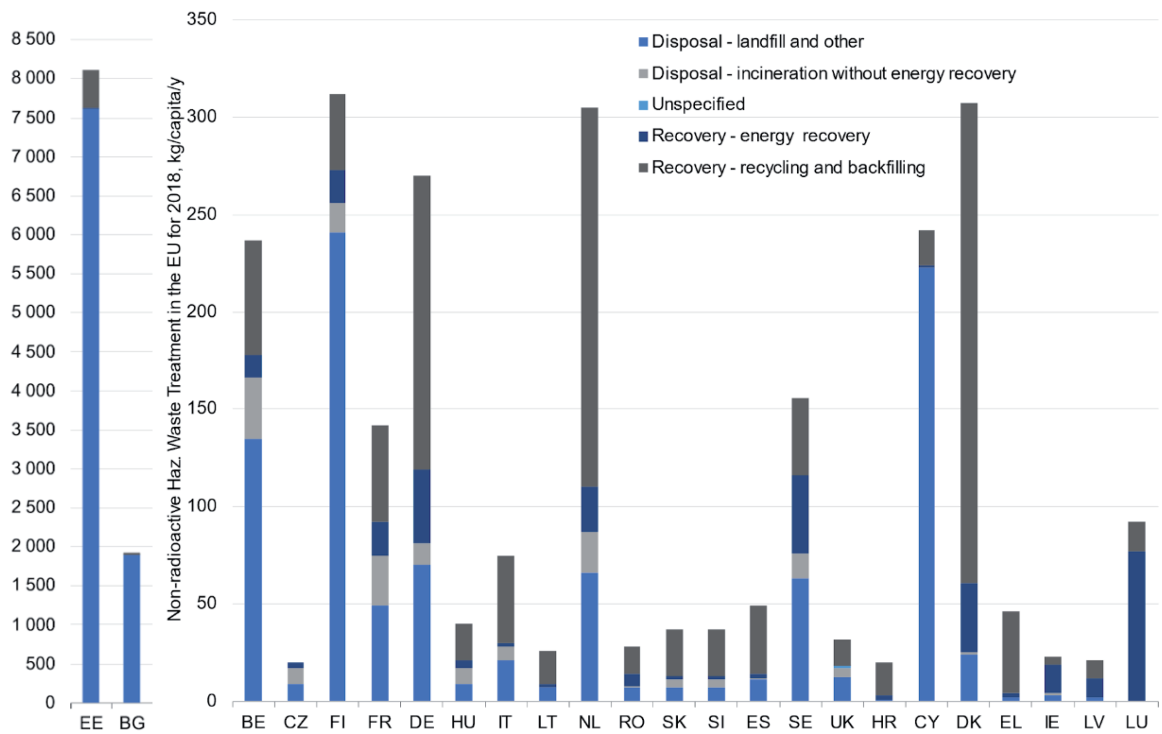

Fig. 5. Non-radioactive Hazardous Waste Treatment in the European Union for 2018: kg/capita/y
(EU28 average 184 kg/capita/y. MSs ordered like in the figure for RW. Source: Eurostat, data code env_wastr. Notice different scale for EE and BG on left because of much larger volumes.) [6]

Zdenko Šimić, Assessing the Scale of the Radioactive Waste Management Problem: A Review of European Union and International Reporting, Journal of Energy, vol. 72 Number 1 (2023), 8–13
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IV. Conclusion

This paper has analyzed selected data on the management of spent fuel (SF) and radioactive waste (RW) at the global and EU levels. Information was gathered from two recent sources: the IAEA Status Report and EU Progress Reports on the Implementation of the Waste Directive. The paper briefly outlines the frameworks, practices, and technologies developed for SF and RW management. It also focuses on the inventory of SF and RW in various regions of the world, including information on the reprocessing of SF, storage methods, and final disposal.

A comparison of the normalized amounts of SF and RW, per capita and per land area, has been made between world regions and EU Member States. The paper also presents an analysis of the density of nonradioactive hazardous waste (HW) at a global and EU level.

The majority of RW has already been disposed of (80% globally and 70% in the EU), however, this only applies to low-level and intermediate-level waste categories. High-level waste and SF have yet to be disposed of (or reprocessed) in any country. Finland is the first country with a deep geological repository for high-level waste and SF, which is currently under regulatory review for an operating license.

The data and normalization show that the cumulative amounts of SF and RW are both absolutely and relatively small and significantly smaller in comparison to the amounts of HW managed annually. The average HW treated yearly per capita, in nuclear EU Member States, is more than 200 kilograms, which is 40 times larger than the average accumulated RW from the beginning of nuclear power use.

RW management is subject to stricter regulations (such as export restrictions) and is certainly more controversial than the management of HW. The amount of HW traded between countries is larger than the total amount of accumulated RW (~40 million/year vs ~38 million tons total, assuming 1 $m^3 \approx$ 1 ton). The transport of RW and SF between countries is rare and primarily related to treatment and reprocessing, with the resulting radioactive waste being returned to the originating country.

Future work could include a more detailed comparison of HW and RW in terms of regulatory oversight and public risk. This could be useful in assessing the cost of waste management in comparison to risk and in potentially improving management including better informing and engaging stakeholders.

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