Radioactive Waste Status - World Regions and European Union Inventory

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ABSTRACT

Information about radioactive waste (RW) management including inventory is available from several sources (e.g., IAEA and European Commission). The IAEA is collecting voluntary national profiles under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The European Commission is requesting reports from Member States in accordance with Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. Every three years findings from these reporting are published by the IAEA and EC. Both sources provide comparable status and trends related to RW policies, frameworks, and programs. Significant focus is related to waste and spent fuel inventories including developed practices and technologies.

This paper is reviewing latest available reports from the Commission (including Commission staff working documents) and the IAEA with focus on the RW inventory and status of its disposal. Paper is presenting some findings related to overall situation in the European Union (EU) and inventory comparison between EU member states including some comparison with the reporting from the IAEA related to the whole world. The presentation of radioactive waste and spent fuel inventories is made with values normalized per person and land area. This was done with intention to improve understanding of the scale of the problem related to RW management. Relative scale of the problem is also illustrated by comparison with inventories for hazardous waste.

There is 264000 t of spent fuel worldwide, which can be expressed as 2 g/km^2 and 0.04 g/capita. Total amount of all categories of radioactive waste is 37.6 million of m^3, and this can be also expressed as 290 l/km^2 and 5 l/capita. Majority of RW (92%) is very low or low level and 81% is already disposed of. In comparison every year about ten times more of hazardous waste is created worldwide (~50 kg/capita/y). These numbers illustrate that amounts of RW are both absolutely and relatively not so big. Status reports, with the high percentage of RW disposed of, are showing that RW is routinely manageable. This is also including the management of high level RW considering that Finland is very soon opening permanent disposal with several other countries following.

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

1 INTRODUCTION

Information about radioactive waste management (RWM) status, including inventory, is available from multiple sources (e.g., IAEA and European Commission). The IAEA is collecting voluntary national profiles under the Joint Convention on the Safety of Spent Fuel (SF) Management and on the Safety of RWM. The European Commission (EC) is requesting reports from Member States (MSs) in accordance with Council Directive 2011/70/Euratom (further on "RW Directive") establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. Every three years findings from these reporting are published by the IAEA and EC. Both sources provide comparable status and trends related to RW policies, frameworks, and programs. Significant focus is related to waste and spent fuel (SF) inventories including developed practices and technologies.

This paper is reviewing latest available reports from the IAEA ([1]) and the Commission ([2], including Commission staff working documents, [3] and [4]) with focus on the RW and SF inventories, and status of its disposal. Paper is presenting some findings related to overall situation in the world and inventory comparison between EU MSs. The presentation of RW and SF inventories is made with values normalized per person and land area. This is not usually done, and hope is to improve understanding of the scale of the problem related to RWM. Finally, the relative scale of the RWM problem is illustrated by comparison with inventories for hazardous waste at both world and European Union (EU) level.

The main objectives of the RW Directive is to assure high safety level of long-term radioactive waste management and to improve transparency (i.e., public information and participation) in the EU. Member states are legally obliged to report on waste directive implementation and inventory status every three years. National programs and reports also allow much easier comparison because they follow common format and requirements. The EC is reviewing submissions and reporting findings to the Council and the European Parliament. The waste directive is covering national policies, frameworks and programs related to all sources of radioactivity including nuclear spent fuel and related inventories. The latest available reporting from the EC is in 2019 covering all MSs (including UK).

The reporting from the IAEA has similar goals with major difference that MSs reporting is voluntary. Their aim is to publish updates every three years in sync to reporting cycle of the Joint Convention. Latest report is from 2022 covering status from the end of 2016 (same as for the EU). Reporting is covering 83 (the number of Contracting Parties, including EU) participating MSs. This reporting is subject to peer review process.

It is outside of the scope for this paper to cover inventory related uncertainties and information about RW generated by military activities. Uncertainties are mainly related to waste categorization and differences during conditioning. Both the IAEA and EC are presenting inventories using the IAEA GSG-1 classification, i.e. Very Low Level Waste (VLLW), LLW, Intermediate Level Waste (ILW) and High Level Waste (HLW). Spent fuel is treated separately because some countries are using or considering reprocessing.

Naturally occurring radioactive materials (NORM) are left out because only some countries are considering them. The NORM issue might become more interesting because of increasing inventories coming from many sources[1]. Similarly, disused sealed radioactive sources are also left out from this paper because not all countries are treating them separately and they are relatively less significant.

This paper is organized in the following way: after Introduction next section is providing highlights about RW and SF status, including inventories. Then Section 3 presents normalized RW, SF and hazardous waste inventories. Final section provides some conclusions.

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

2 RADIOACTIVE WASTE AND SPENT FUEL STATUS HIGHLIGHTS

This paper has narrow focus related to SF and RW inventories. For completeness here are some highlights about other findings related to SF and RW management. To avoid repetitive referencing, it should be assumed that world related information is taken from the IAEA status and trend report about SF and RW management, [1]. This includes inventories information about EU. Some specific findings related to the EU are taken from the Waste Directive related EC reporting and EC staff working documents, (i.e., [2], [3] and [4] respectively).

More comprehensive information about SF and RW status, sources and supporting materials, is available in the IAEA status report. Similarly, plenty of additional information about EU MSs implementation of Waste Directive requirements is available from the EC report and related documents.

In the first subsection SF and RW management frameworks are briefly presented. The second subsection is providing some high-level information about developed practices and used technologies.

2.1 Frameworks for the management of SF and RW

A basic principle, stated by the EU (Waste Directive), Joint Convention and the IAEA (fundamental safety principle), is that prime responsibility for SF and RW safety rests with license holder. However, the state has responsibility for ensuring that necessary programs are prepared. These obligations are implemented through legislation and regulation with defined roles and responsibilities for all involved.

The governments are establishing legal and regulatory framework with defined responsibilities and provisions to ensure funding, management (facilities etc.) and public involvement. Clear separation of regulatory body from the ministry in charge of energy (or industry) is preferred (practice in most EU and OECD/NEA countries).

National policy is expected to address the following: responsibilities, financial arrangements, preferred management options (including for decommissioning), and public involvement. National strategy(ies) is developed (usually by the established waste management organizations, WMO) to implement policy (develop facilities, define targets and roles). WMO could be state (separate or part of the research/government organization) or private organization (usually utility). Regulatory body and/or responsible ministry is usually approving strategy.

It is common that RWM funds have state oversight and are held in account outside waste generation companies with state oversight. In most countries, with operating nuclear power plants, dedicated upfront financial system is in place. Cost of SF and RW management, including decommissioning, presents relatively small contribution to the price of produced energy.

Final waste disposal is expected (by both Joint Convention and Waste Directive) in the country where it is generated. The export and import of SF and RW are prohibited in many states with exceptions e.g. related to reprocessing and treatment services. Return of disused sealed radioactive sources (DSRS) is also usually arranged with suppliers.

Early involvement of stakeholders from start (through the life cycle of the nuclear facility, storage and final disposal) is critical. Disposal facilities are in operation for decades and they present potential hazard for hundreds to thousands of years (depending on RW category). Waste Directive ensures the provision of necessary public information and participation. Various international conventions also cover stakeholders involvement: e.g., Aarhus (access to information, decision-making participation, and environmental justice) and Espoo (transboundary environmental impact) Conventions.

2.2 Developed practices and technologies

RWM covers the whole life cycle including facility operation, RW generation, characterization, treatment, storage, and final disposal. RW reduction (from primary, secondary and recycling sources are part of the management). Potential for recycling and reuse is limited nationally. Final disposal is defined as intentional emplacement with passive engineered and natural isolation without plan for retrieval (with possibility in some countries). SF and RW management is highly regulated and there are internationally developed and accepted safe technical solutions.

SF is mostly kept in wet or dry storage waiting for final solution which might be reprocessing or direct disposal. Only few countries are currently reprocessing SF (France, Japan, and Russia)[2]. Some countries are using SF reprocessing service. China is operating pilot reprocessing plant. SF reprocessing results in, usually vitrified, HLW ready for final disposal. In both cases final disposal is planned in similar way like for the long lived ILW and HLW, in deep geological repositories. In some countries this might include plans for possible retrieval.

New storage facilities for SF are built further away from reactor and can be even outside boundaries of the plant. For longer storage different types of dry solutions are now more and more used. The canisters of HLW, after reprocessing are stored in air cooled vaults or casks like those used for SF.

Finland is the first country to reach operating license submission stage for deep geological repository (DGR, 400 m and deeper) with prospect to start accepting SF in few years. Several other countries are in different licensing stages for their DGRs (France, UK, Canada, and Germany). Sweden recently issued construction license for their GDR. There is about 20 underground research laboratories in use for SF and HLW DGRs (e.g., HADES in Belgium, KURT in R. of Korea, and Krasnoyarsk in Russian F.).

ILW usually contains significant amounts of long-lived radionuclides and therefore requires shielding during handling and deeper locations for final disposal. Treatment and conditioning of ILW includes separation, volume/size reduction and stabilization prior to packaging. This includes, when needed, drying, evaporation, high compaction, melting and cementing. Concrete containers with steel reinforcement, steel boxes and drums are used for ILW packaging. Storage is considered for longer period (up to 100 years) before final disposals is available. Heat removal is usually not required. In general, ILW disposal is safe at about 100 m under the surface. One licensed disposal facility is operating in the USA (Waste Isolation Pilot Plant). Many countries (e.g., Germany, Switzerland, and France) are planning to dispose ILW together with HLW in DGRs.

LLW shares in principle many similarities with ILW regarding treatment and storage. Especially important for LLW compacting is incineration. Longer term storage is also usually considered. Major difference with ILW is much larger volume and lower radioactivity of LLW. Most of LLW radionuclides have half-life of less than 30 years. Many countries are disposing of large volumes of LLW in near surface repositories (e.g., UK, Spain, France, Japan, USA) or in caverns below ground level (Sweden, Finland) for many decades. Engineered barriers are preventing water infiltration and intrusion. Surveillance is planned for few hundred years. Some countries are disposing of LLW (e.g., Sweden, Finland, Hungary, Czech R., Germany, Romania) or planning (Canada, Netherlands) to dispose of at deeper locations (50÷100 m). Some countries are considering disposing of LLW by collocating it with ILW. While this approach requires smaller number of repositories it could be more complex because of higher volume and additional requirements.

Finally, VLLW waste is mainly related to decommissioning (concrete, soil and rubble) and separately treated only by some countries (e.g., France, Japan, Lithuania, Spain and Sweden). There is little processing for LLLW except for packaging and potential separation for clearance (where used). Simpler shelter or temporary cover is sufficient for LLLW storage. Final disposal is facility in

[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.

shallow trenches (e.g. in France, Slovakia and Spain) or above ground design with concrete slab (e.g. Sweden and Lithuania). Some countries dispose of VLLW together with other LLW or other non-nuclear hazard waste (UK).

There is significant experience and progress in disposing of LLLW and LLW with disposed volumes much higher than stored volumes.

The most important aspects are related to plans for addressing long term knowledge management and preservation together with transparency and involvement of stakeholders. For this, as well as for technology and experience, active international cooperation, research and development are very important.

2.3 SF and RW Inventories

The RW classification differs (as mentioned before) in some countries and preparation of total amounts required conversion based on the information provided by countries or with some assumptions. This adds some uncertainty. Global data is here presented by regions (at higher level in comparison to previous IAEA status report). More detailed information at country level is available in references [1]÷[4].

Table 1 provides cumulative amounts of SF in wet and dry storages across world regions, including reprocessing, in 1000 t of heavy metals (HM). Table 2 presents cumulative amounts of RW for all categories in 1000 m3. Table also provides share of RW already disposed of. Values for EU MSs are presented both in European region and separately.

SF from the research reactors is not presented in detail because of much smaller quantities and for brevity. DSRSs are also not covered here for similar reasons and because some countries treat them together with respected RW categories. In many countries DSRS are the primary or only type of RW.

Globally there is 390000 tHM of SF (43% in the EU) including reprocessed (one third of total and 68% in the EU).

Table 1: 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**

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

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

Globally, there were 448 reactors operating (with net capacity of 391 GWe) in 30 countries at the end of 2016. In the EU 14 MSs have nuclear power plants in operation (119 GWe in 126 reactors) and together with Italy and Lithuania (who terminated their nuclear program) they account for 99.7% of RW volume. Three reactors are decommissioned and 90 are shut down. There are 82 research reactors (including those in decommissioning) in the 19 MSs.

Table 2: Reported Solid Radioactive Waste (1000 m^3, end of 2016), [1]

REGION	VLLW		LLW		ILW		HLW
1000 m^3	Total	Disposed	Total	Disposed	Total	Disposed	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

The volume of RW is increasing with nuclear power plants operation at rate of about 2% per year (comparison with previous years is complicated with changes in reporting related to RW classification etc.). Additionally, this volume depends significantly on technologies used for conditioning, storage, and disposal. Larger amounts of LLLW and LLW are expected to be generated soon because of increased number of plants to be decommissioned. So far globally less than 20 reactors have been decommissioned. At the end of 2016 there was 123 reactors in decommissioning process with large number expected to be decommissioned because more than 140 operating reactors are older than 40 years (they usually get extended operating time to 50 or 60 years).

3 NORMALISED COMPARISON WITH HAZARDOUS WASTE

Comparison between RW and other hazardous waste (HW: toxic, corrosive, biological, explosive, and flammable) could improve management and even perception about related problems. This comparison could include regulation, trade, toxicity, presence in the environment and longevity. This paper is starting this complex comparison with focus on the amounts of RW and HW. This comparison is done by estimating the amount of waste per capita[3] and land area[4]. Estimates are made first for RW using world regional and country (for EU MSs) data. Then global HW and EU MSs data are used to present amounts per capita.

Globally about 400 million tons of HW is produced annually (total amount of all waste is estimated to be about 20 times larger), [5]. Trading with HW between countries is growing and currently estimate is to be about 40 million tons of HW per year.

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

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

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

[3] World population by regions: ourworldindata.org/grapher/historical-and-projected-population-by-region; and EU population change, eurostat: bit.ly/EUpopulation

[4] Regions in the world (with area): www.worldometers.info/world-population/population-by-region/; and for the EU MSs: en.wikipedia.org/wiki/Member_state_of_the_European_Union.

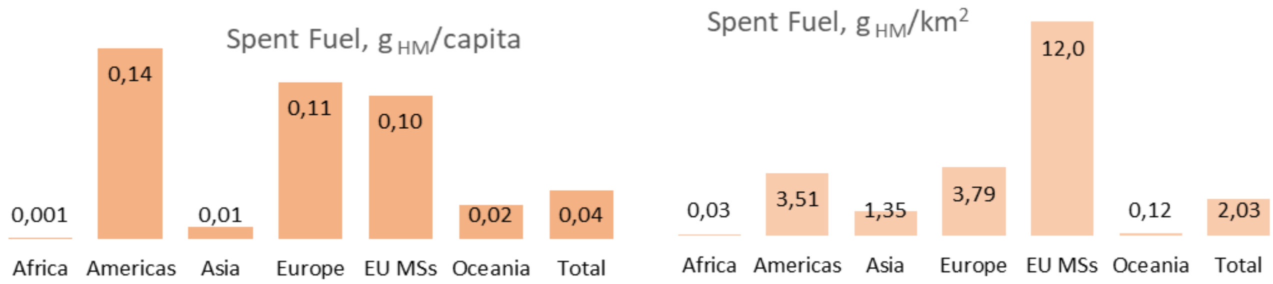

Figure 1: Accumulated Spent Fuel, World Regions: kg $_{HM}$/capita and g $_{HM}$/km^2 (HM – Heavy Metal)

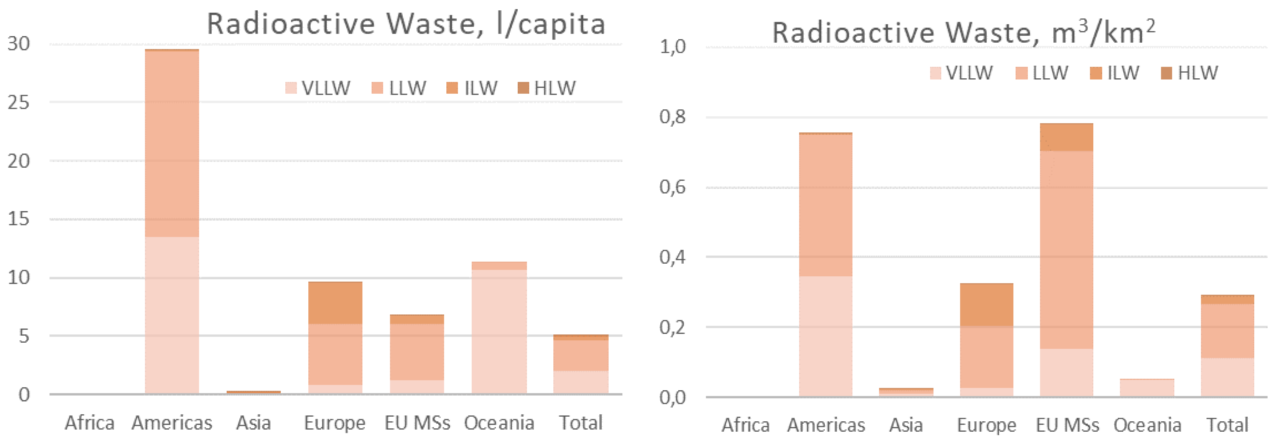

Figure 2: Accumulated Radioactive Waste, World Regions: l/capita and m^3/km^2, [1]

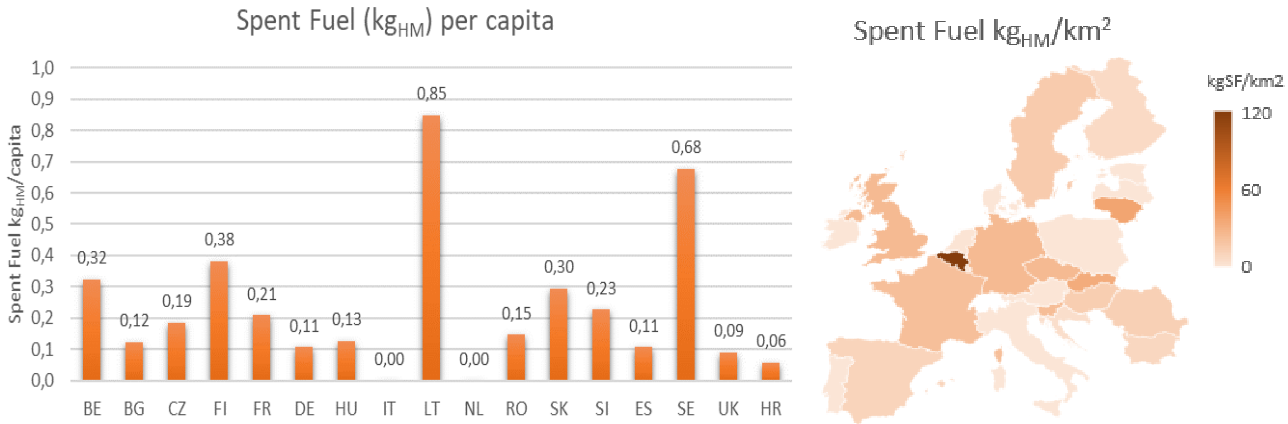

Figure 3: Accumulated Spent Fuel in the European Union: kg $_{HM}$/capita (MSs with nuclear program) and kg $_{HM}$/km^2 (HM – Heavy Metal. Data for HR include share from the SI.), [4]

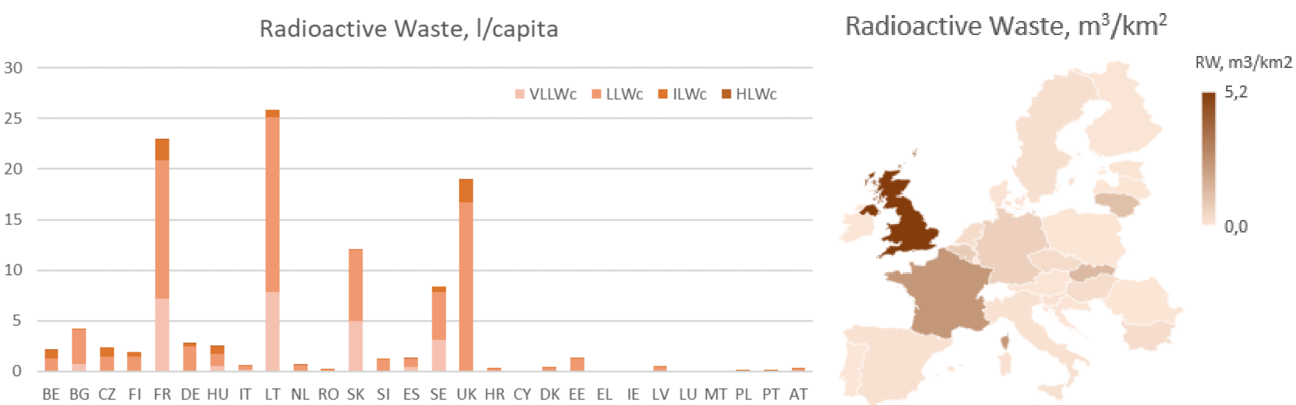

Figure 4: Accumulated Radioactive Waste in the European Union: l/capita and m^3/km^2 (Data for HR include share from the SI.), [4]

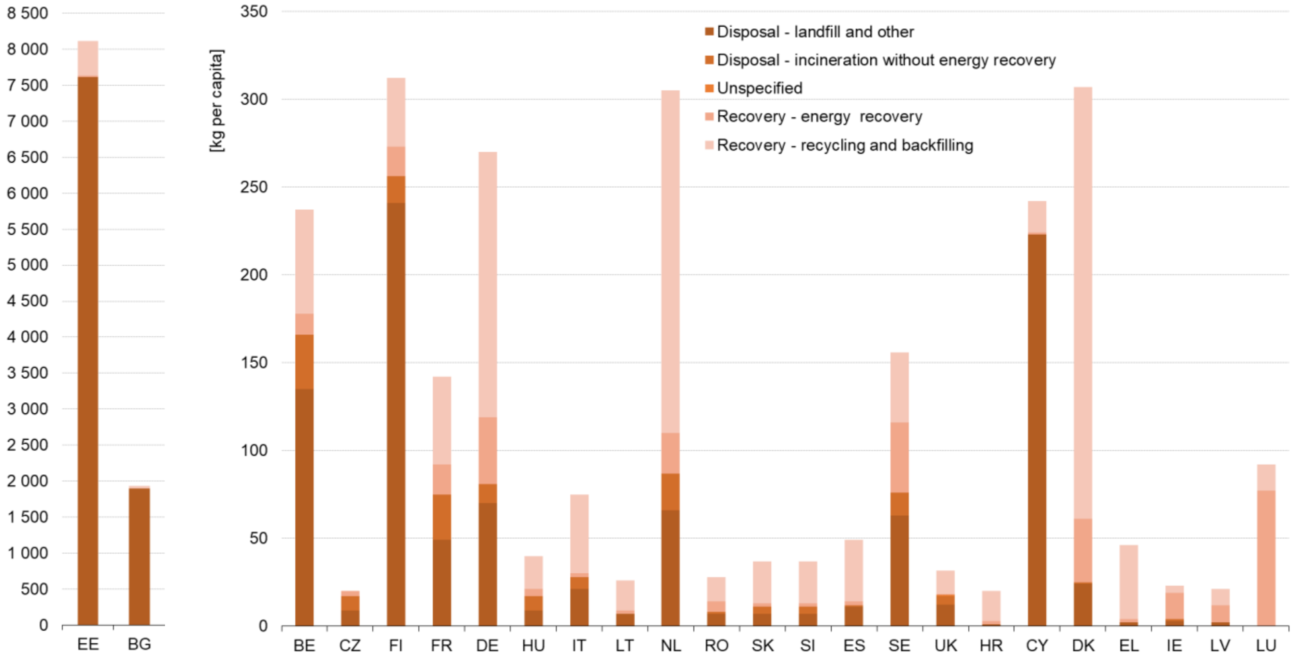

Figure 5: Hazardous Waste Treatment in the European Union for 2018: kg/capita/y
(EU28 average 184 kg/capita/y. MSs ordered like in figure for RW. Source: Eurostat, data code: env_wastr.), [6]

It might be interesting to estimate how much of SF and RW would be per every person in imaginary scenario for the lifetime where only nuclear power was used to produce electricity. This evaluation depends on many assumptions, and for approximate estimate it seems reasonable to judge, based on here presented data for EU MSs, that burden would be somewhere in the order of about 1 kg of SF and about 30 liters of RW (including about 3 l of ILW and half liter of HLW) per capita.

Based on the global hazard waste amounts it can be estimated that every year is produced about 50 kilograms per person. Detailed data for world regions are not easy to obtain. Country statistics about RW for the EU MSs is available. Figure 5 shows the amounts of HW treated every year in EU MSs in kilograms per person. About half of MSs have amounts which are comparable with global average. However, eight MSs have amounts larger than 200 kg/capita/year.

These data show how amounts of HW generated per person every year are abouy 10 times larger than amounts of RW cumulatively generated from the beginning of the use of nuclear power (after more than 50 years).

4 CONCLUSION

This paper has presented selected data about spent fuel and radioactive waste management at global and EU level. Two latest sources were used: IAEA status report and EU progress reports on Waste Directive implementation. The paper first briefly presented highlights related to SF and RW management frameworks, developed practices and technologies. The paper is about SF and RW inventory at world regions (including values related to SF reprocessing, type of storage and final disposal).

The paper also presented analysis of normalized amounts of SF and RW, per capita and land area, at world regions and EU MSs level. Finally, paper presented simple analysis of hazardous waste density for the whole world and EU MSs.

Majority of RW by volume is disposed of (80% globally and 70% in the EU). However, this percentage is so high only for the LLLW and LLW categories while HLW and SF are not yet disposed of in any countr. Finland is the first country with ready deep geological repository, for HLW and SF, under regulatory review for operating license.

Presented data and normalization illustrate how cumulative amounts of SF and RW are both absolutely and relatively not so large and significantly smaller in comparison to amounts of yearly treated HW. Yearly treated HW average per capita, for nuclear EU MSs, is >200 kg, which is about 40 times larger than average of accumulated RW from the beginning of nuclear power use.

Management of RW seems more strictly regulated (e.g., export restrictions) and certainly is way much more controversial than for HW. The amount of every year traded HW between countries is larger than total amount of accumulated RW (~40 vs ~38 million t, assuming $1m^3 \approx 1t$). Transport of RW and SF between countries is rare and dominantly related to treatment and reprocessing with return of resulting RW to origin country.

Future work might be more detailed comparison of HW and RW related to regulatory scrutiny and public risk. This might be useful for assessing the cost of waste management in comparison to risk and perhaps to improve management and help better informing and engaging stakeholders.

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