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Investigation into the Current State of Nuclear Energy and Nuclear Waste Management—A State-of-the-Art Review

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Abstract: Nuclear power can replace fossil fuels and will have a decisive impact on the change in the approach to conventional energy. However, nuclear (or radioactive) wastes are produced by the operation of the nuclear reactors should be safely and properly disposed of. This paper assesses the uranium resources and the global state of nuclear power plants and determines the energy mixes in different countries using the most nuclear energy. Furthermore, this paper analysed the nuclear waste management and disposal and the depletion of abiotic resources, and the primary energy sources of a basic production process using electricity mix and nuclear electricity for a basic production (PET bottle manufacturing) process. The life cycle assessment was completed by applying the GaBi 8.0 (version 10.6) software and the CML method. In this study, we limit our discussion to high-level nuclear waste (HLW) and spent nuclear fuel (SNF) waste. We do not consider waste generated from uranium mining and milling, which is usually disposed of in near-surface impoundments close to the mine or the mill. The investigation of waste management methods is limited to European countries. This research work is relevant because determining abiotic resources is important in a life cycle assessment and current literature available on LCA analysis for nuclear powers remains under-developed. These results can guide and compare manufacturing processes involving a nuclear electricity and electricity grid mix input. The results of this research can be used to develop production processes using nuclear energy with lower abiotic depletion impacts. This research work facilitates the industry in making predictions for a production-scale plant using an LCA of production processes with nuclear energy consumption.

Keywords: nuclear waste; spent nuclear fuel; waste management; life cycle assessment; abiotic resource depletion; electricity mix; nuclear energy

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1. Introduction

Fossil fuel resources (natural gas, oil, and coal, including hard and brown coals) do not have substitutes that can meet the current energy demand. However, at current production levels, documented reserves of oil, natural gas, and coal will be sufficient for 51, 53, and 153 years of operation, respectively [1]. For nuclear energy based on uranium fission, uranium from Reasonably Assured Resources (RAR) will suffice for less than 100 years at the present market price, i.e., no more than the fossil resources, but it could be available for several thousand years if recovered from seawater, albeit at a much higher price. In the same spirit, uranium from Reasonably Assured Resources could suffice for tens of thousands of years if the present thermal neutral reactors were completely replaced by a fleet of fast neutron reactors [2]. Therefore, we need to create a stable energy portfolio if we are to meet the future demand for clean energy. In any case, the future energy portfolio ought to efficiently adapt to alternative energy resources, with renewable sources (wind, solar, biofuels, etc.) poised to replace coal, oil, and natural gas. It should also consider providing access to those without electricity, and those whose lives are devoid of clean cooking facilities. A future energy portfolio should prevent additional air pollution, which causes the premature deaths of far too many people worldwide [3].

Recent developments have created the potential for clean, sustainable, and renewable energy in some countries. Renewable energy offers a better option in terms of cost, reliability, and efficiency. Renewable energies continue to take priority as the energy sector implements established technologies and integrates them within the energy system [4]. One significant problem to solve involves answering to what extent renewable energy resources play a part in power generation. Previous studies arrived at varying conclusions. Reducing energy demand in the short term is an important element of cost-effective mitigation strategies that provide more flexibility to reduce CO_2 emissions in the energy supply sector. According to the baseline scenarios assessed in AR5, direct CO_2 emissions from the energy supply sector will almost double or triple by 2050 compared to 14.4 Gt CO_2 per year in 2010 [3]. Recent developments have created the potential for clean, sustainable, and renewable energy in some countries. Renewable energy offers a better option in terms of cost, reliability, and efficiency. Renewable energies continue to take priority as the energy sector implements established technologies and integrates them within the energy system [4]. One significant problem to solve involves answering to what extent renewable energy resources play a part in power generation. Previous studies arrived at varying conclusions. While a few studies indicated that ~40% of energy demand from variable renewable sources was optimal, others indicated the potential for 75%. The availability of fossil fuels alone will not be enough to limit its CO_2 concentration to 450–650 ppm [3]. For developed countries, scenarios show that changing lifestyles and behaviors could reduce energy demand by up to 20% in the short term and up to 50% by the middle of the century [5,6].

Nuclear power can replace fossil fuels to decisively impact a change in traditional energy approaches. According to many research studies [7–9], over the past two decades, approximately 11–20% of the world's energy requirements were met by nuclear energy. The number of energy plants utilizing coal, oil, and natural gas has increased to such an extent that reducing carbon emissions by 80% or more by 2050 would be incredibly difficult. Nuclear energy does not pollute the air through harmful emissions, does not produce greenhouse gases, and alleviates overexploitation of other fuel reserves. As the demand for energy in the world increases at an alarming rate, both developed and developing economies seek access to stable and clean energy sources in cost-effective and enviro-friendly ways. The major benefits of nuclear power are that they consume less energy, use low-cost, high-efficiency materials, and does not emit greenhouse gases [10]. Therefore, it is the only stable baseload power source that does not harm the environment. Moreover, power generation by nuclear energy remains consistent as the demand for raw materials, such as natural gas and oil, continues to rise.

Nuclear power plants (NPPs) produce negligible quantities of waste compared to other energy sources. Based on the calculations provided by the International Atomic Energy Agency (IAEA), if spent nuclear fuel (SNF) is not reprocessed, a 1000 MW(e) nuclear reactor produces around 30 tons of high-level solid packed waste annually. However, a 1000 MW(e) coal plant annually produces 300,000 tons of ash [11]. Although the quantity of waste produced by the NPPs is small relative to other electricity production methods, they produce high-level nuclear waste (HLW) that has several undesirable characteristics and environmental risks [12]. Therefore, proper management and safe decommissioning of HLW and SNF are the major aspects of energy production by NPPs. SNF waste constitutes the largest portion of high-level nuclear from countries that operate an open fuel cycle strategy. SNF may be considered either as waste, which will eventually be packaged and disposed of, or reprocessed to recover uranium and plutonium followed by the conditioning of residue in the form of HLW containing mainly fission and activation products, and so-called minor actinides.

Several countries, instead of reprocessing the SNF, plan to dispose it of in deep geological formations. The increasing bulk of the SNF stream will be problematic as the use of nuclear power increases. To develop sustainable, permanent, solutions for radioactive waste (RW) and SNF management and decommissioning, it is very important to have a strategic plan, direction, and funds in place. Nuclear recycling is the most effective method to solve this problem. The first step in nuclear waste (NW) management is recycling it, followed by additional processing, storing, and isolation. Furthermore, recycling helps reduce hazardous waste storage and reduces environmental pollution. According to Wallenius [10], efficient recycling of HLW from SNF decreases ~4–6% of the waste repository volume and decreases the amount of time required (by a factor of 100) during the isolation of residual waste.

The European Green Deal and the Sustainable Development Goals (SDGs) require a more holistic approach to production processes. The growing importance of environmental protection and waste management has enlarged interest in the development of the life cycle assessment (LCA) method. Life cycle assessment is a widely used method to assess the environmental impacts of product life cycles and their technological processes, as well as waste management systems and waste disposal processes. Life cycle assessment measures environmental burdens with the help of impact categories, resources, and emissions into the environment [13]. According to the International Reference Life Cycle Data System (ILCD) and the Product Environmental Footprint (PEF) [14,15], abiotic depletion potential (ADP) is one of the most debated environmental impact categories in LCA. The abiotic depletion potential covers some selected natural resources such as metal-containing ores, crude oil, and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. The abiotic depletion potential is typically split into two sub-categories, elements and fossil (i.e., energy) [16]. Abiotic depletion potential for elements (ADPE) covers an evaluation of the availability of natural elements such as minerals and ores, including uranium ore. Even though uranium is also an energy carrier, uranium extraction is classified as an abiotic resource depletion for elements. The reference substance for the characterization factors is typically antimony. Resources in the fossil fuel impact category include oil, natural gas, and coal, which are all energy carriers and mutually substitutable. Consequently, the total amount of fossil fuels form the fossil fuel stock and is expressed in MJ. Considering the Planetary Boundaries (PBs) structure, life cycle assessment creates an affiliation between the SDGs and the European Green Deal [17].

The first aim of this research was to analyze uranium resources and nuclear energy production focusing on the energy mix of different countries based on many reviewed papers. First, we made different tables for nuclear energy distribution in countries using the most (above 30%) nuclear energy in 2017–2018 and for the global state of nuclear power plants by countries. Electricity mix data from various countries in 2021 was unavailable; therefore, we created pie charts based on the database from GaBi 8.0 software. Furthermore, another goal of this research work was to calculate the ADPE for a basic production technology (production of PET bottles from PET granules) with the help of energy inputs from the electricity grid mix (scenario 1) and only from nuclear electricity (scenario 2) for eleven different countries.

This paper presents a life cycle assessment methodology including the scenarios, determination of the abiotic depletion resources for elements, allocation method, and applied software. It gives a description of the life cycle inventory (LCI) methodology and explains the life cycle impact assessment (LCIA) method. The main section explains the research results, and the last section summarizes the conclusions.

This article introduces and investigates literature data for uranium production and nuclear energy plants, abiotic resource depletion, and primary energy resources for a basic production process.

2. Materials and Methods

2.1. Data Research Methods

This manuscript is partly based on primary literature data and partly on secondary industry data from GaBi 8.0 life cycle assessment. This review follows a lengthy literature review we published that covered data from the following sources—World Nuclear Association, International Atomic Energy Agency (IAEA), Power Reactor Information System (PRIS), and the European Commission. In calculating the electricity grid mix to represent using pie charts from different countries, we used specific information from the GaBi 8.0 life cycle assessment software. The related life cycle inventory includes and quantifies energy supplies for all countries examined. The dataset for the electricity mix is an annual average in 2021.

2.2. Life Cycle Assessment Method

One goal of this research was to determine abiotic depletion as an environmental impact category and primary energy resources for the production life cycle of polyethylene terephthalate (PET) products using a professional dataset. After quantifying the abiotic resource depletion, the life cycle analysis was conducted using GaBi 8.0 (version: 10.6) software (by Sphera Solutions Ltd., Stuttgart, Germany). Modeling a plastic product requires the use of product-specific input data. The Life Cycle Inventory (LCI) method includes and quantifies the input-output material flow and the energy requirements of unit manufacturing. This methodology divides the energy requirements and environmental emissions between the PET products produced by mass allocation. The dataset for polyethylene terephthalate corresponds to the EU average. The inventory is primarily based on industry data from internationally relevant production processes. During manufacturing, we assumed no manufacturing loss. Output was used to determine the abiotic resource depletion and primary energies of 4 kg of PET. Using the CML life cycle impact assessment method (developed by the Centre for Environmental Science at Leiden University, Leiden, The Netherlands), we determined the abiotic resource depletion and primary energies. During that analysis, the reference system utilized the electricity energy inputs for each country. We did not use normalization and weighting to calculate the magnitude of impact category indicators.

3. Results

3.1. Uranium Resources and Uranium Production

The exact processes of nuclear fuel or spent fuel differ depending on the nuclear fuel cycle technologies utilized. Currently, single and dual fuel cycles are the primary strategies: the once-through cycle (direct disposal or open cycle) and the twice-through cycle (recycling or partially closed cycle). Based on this, nuclear fuel production cycles for both technologies include natural uranium extraction (uranium mining and milling), conversion, and enrichment; the nuclear fuel fabrication cycle for both technologies include natural uranium mining (uranium mining and milling), conversion, enrichment, and fuel fabrication. Figure 1 shows the mass flows during nuclear fuel production.

In 2018, uranium production surpassed 53.4 tons. Table 1 gives the amount of uranium production in 2018 by different countries. This table shows that more than 40% of all uranium production came from four countries (Kazakhstan, 41%; Canada, 13%; Australia, 12%; and Namibia, 10%). Figure 2 gives the 2018 worldwide distribution of uranium production.

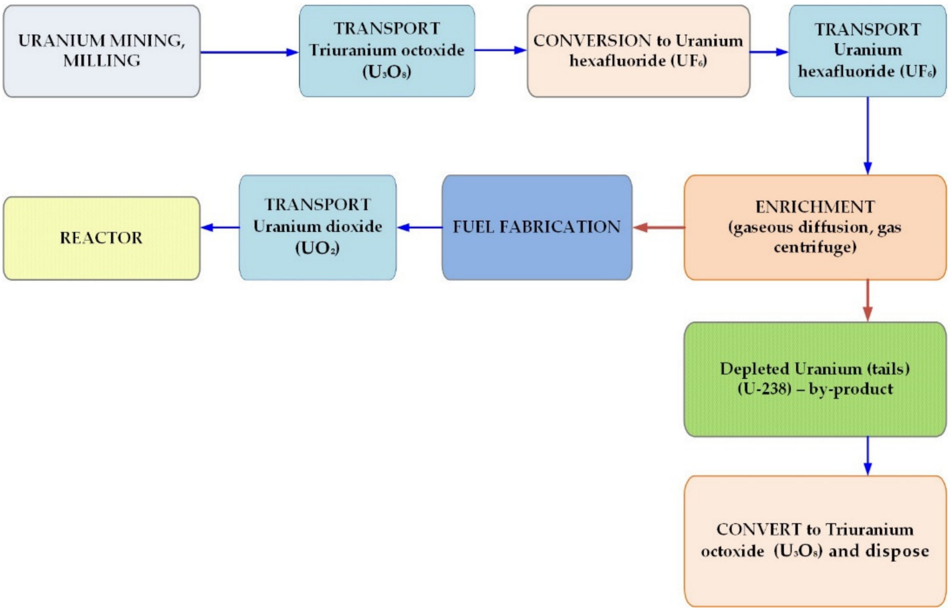

Figure 1. Mass flows in nuclear fuel production.

Table 1. Total uranium production by counties in 2018 [18].

Country	Uranium Tons	Weight Percentage %
Kazakhstan	21,705	40.57
Canada	7001	13.09
Australia	6517	12.18
Namibia	5525	10.33
Niger	2911	5.44
Russia	2904	5.43
Uzbekistan	2404	4.49
China	1885	3.52
Ukraine	1180	2.21
USA	582	1.09
India	423	0.79
South Africa	346	0.65
Iran	71	0.13
Pakistan	45	0.08
World total	53,499	100.00

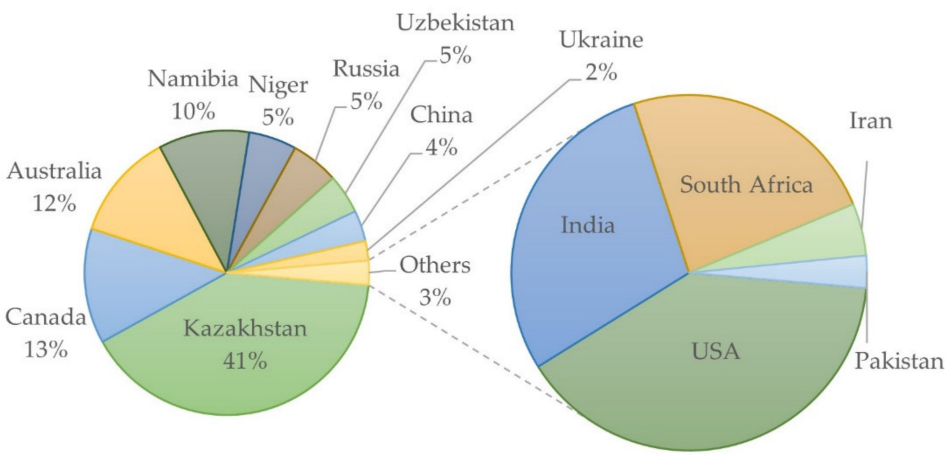

Figure 2. Distribution of worldwide uranium production in 2018 [18].

3.2. Nuclear Energy Production

According to a new publication [19] from the International Energy Agency (IEA), the planet's demand for electricity is booming this year and next, after falling by about 1% cent in 2020. The IEA's recent report on the electricity market indicates that global electricity demand jumped nearly 5% in 2021 and 4% in 2022. In terms of carbon emissions from the electricity sector, the IEA forecasts growth of 3.5% in 2021 and 2.5% in 2022. Fossil fuels continue to dominate. In 2022, fossil fuel-based electricity generation will cover 40% of demand. In 2021, coal was responsible for 34% of the world's electricity generation, while gas accounted for 25%. Renewable energy and nuclear energy together accounted for 37%. According to the IEA's central scenario (New Policies Scenario), the share of the world's nuclear power plants in total electricity generation will remain long-term at 12% [19]. According to the IEA, renewable energy sources will be able to serve only half of the expected growth in global demand in 2022. Hydropower provided 17% of the World's electricity generation, which was the third largest source after coal and natural gas. Global hydropower capacity could increase by 17 percent or 230 gigawatts between 2021 and 2030. Renewable energy is growing impressively in many parts of the world, but it is still not at a level to reach zero net emissions by the middle of the century [19]. Table 2 shows the global state of nuclear power plants in 2022 by reactor type groups. Table 3 represents nuclear power plants in countries that will operate and design nuclear reactors in February 2022.

Table 2. Global state of nuclear power plants by reactor type in 2022 [20].

Reactor Type Groups	Connected to the Grid (2022)		Under Construction (2022)		Shutdown	
	Capacity (MWe)	Units	Capacity (MWe)	Units	Capacity (MWe)	Units
BWR	61,849	61	2653	2	30,670	52
FBR	1400	3	1412	3	1951	8
GCR	5650	10	-	-	9307	42
HTGR	200	1	-	-	679	4
HWGCR	-	-	-	-	169	3
HWLWR	-	-	-	-	398	2
LWGR	7433	11	-	-	8924	13
PHWR	24,404	48	1890	3	2723	10
PWR	292,917	307	48,562	45	41,271	63
SGHWR	-	-	-	-	92	1
Others	-	-	-	-	87	2
Total	393,853	441	54,517	53	96,271	200

Table 3. Global state of nuclear power plants by country (February 2022) [World Nuclear Association], [IAEA Power Reactor Information System], [21].

Country	Existing Units	Capacity (MWe)	Units under Construction
Argentina	3	1641	1
Armenia	1	415	0
Belarus	1	1110	1
Bangladesh	0	0	2
Belarus	1	1110	1
Belgium	7	5942	0
Brazil	2	1884	1
Bulgaria	2	2006	0
Canada	19	13,624	0
China	54	50,789	14

Table 3. *Cont.*

Country	Existing Units	Capacity (MWe)	Units under Construction
Czech Republic	6	3934	0
Finland	4	2794	1
France	56	61,370	1
Germany	3	4055	0
Hungary	4	1914	0
India	23	6885	6
Iran	1	915	1
Japan	33	31,679	2
Korea RO (South)	24	23,136	4
Mexico	2	1552	0
Netherlands	1	482	0
Pakistan	5	2242	1
Romania	2	1300	0
Russia	38	28,578	4
Slovakia	4	1868	2
Slovenia	1	688	0
South Africa	2	1860	0
Spain	7	7121	0
Sweden	6	6882	0
Switzerland	4	2960	0
Turkey	0	0	3
Ukraine	15	13,107	2
UAE	2	2762	2
United Kingdom	11	6848	2
USA	93	95,523	2
World total	436	387,866	52

Based on statistical data from the World Nuclear Association [22], 62% of the operating reactors worldwide are at least 30 years old. Consequently, the decommissioning of nuclear facilities has become increasingly more important as more and more reactors are shut down or scheduled for shuttering. Table 4 summarizes the nuclear energy distribution in total energy consumption for countries using the most (weight percentage above 30%) nuclear energy in 2017 and 2018. There is no literature available on electricity use in different countries for 2021; therefore, we considered the importance of creating and illustrating based on the professional database of 2021 from the GaBi 8.0 software.

Table 4. Distribution of nuclear energy in total energy consumption in the countries using the most (above 30%) nuclear energy in 2017 and 2018 (source: World Nuclear Association), and 2021 (source: GaBi 8.0 database).

Country	2017 %	2018 %	2021 %
Bulgaria	34.11	34.70	34.80
Czech Republic	32.59	34.50	35.30
Finland	33.49	32.50	34.80
France	70.95	71.70	77.60
Hungary	49.10	50.60	53.40
Slovakia	54.67	55.00	56.80
Slovenia	38.49	35.90	36.50
Sweden	40.00	40.30	42.20
Switzerland	32.30	37.70	38.40
Ukraine	54.00	53.00	54.86
Belgium	48.80	39.00	46.60

Figures 3–6 illustrate (using pie charts) the electricity grid mix for countries with >50% nuclear energy use (France, Slovakia, Ukraine, and Hungary) in 2021. Electricity mixes were modeled according to country-specific situations. Here, the electricity from nuclear energy is a mix of pressurized water (PWR) and boiling water (BWR) reactors. The pie charts represent an average country-specific electricity supply, which included electricity consumption, transmission/distribution losses, and electricity imports. Individual renewable energy sources were calculated according to the current national electricity grid mix. The electricity provided by non-combustible renewable energy sources is also considered national or regional situations, such as solar radiation (photovoltaic), annual full load hours (wind power), and share of hydropower stations. The data of these electricity mixes can be used for life cycle assessment studies, energy models, and combination/optimization of technological processes.

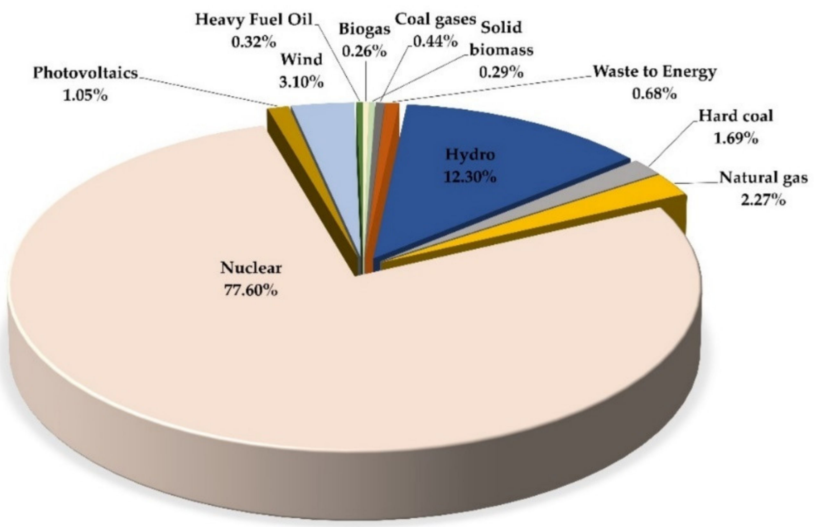

Figure 3. Electricity mix for France (2021). (Source: GaBi 8.0 database).

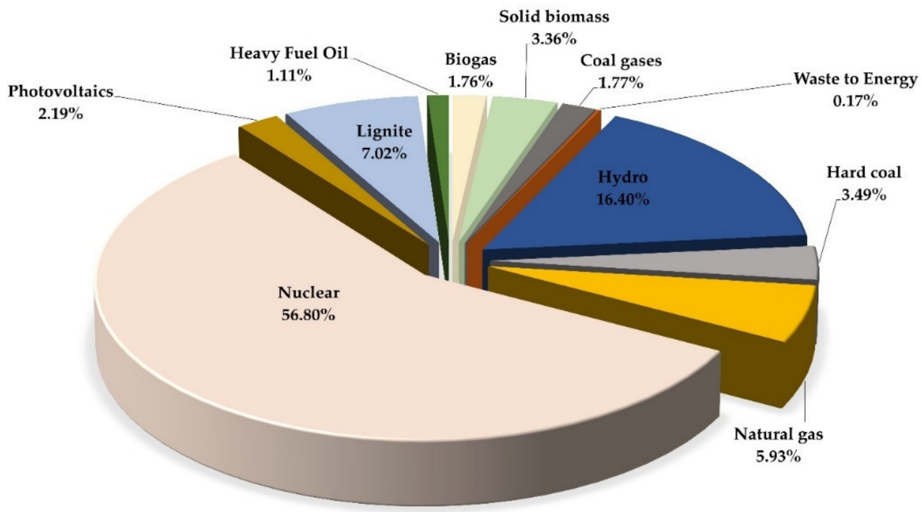

Figure 4. Electricity mix for Slovakia (2021). (Source: GaBi 8.0 database).

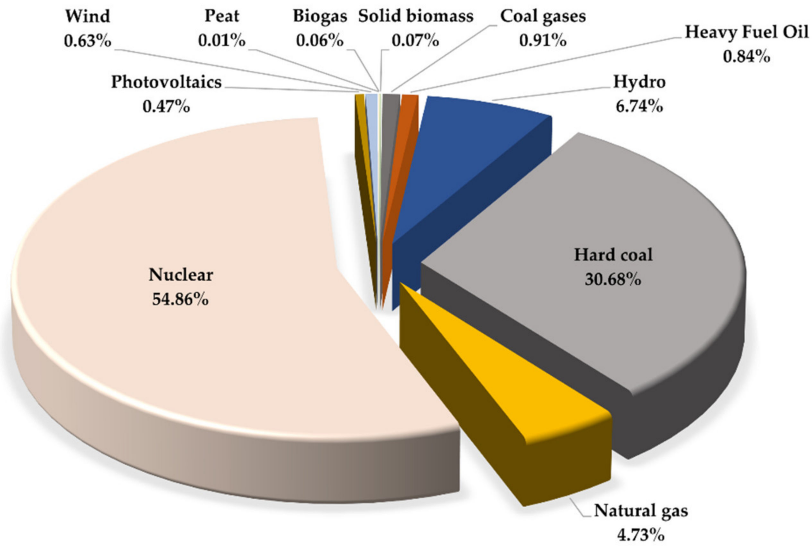

Figure 5. Electricity mix for Ukraine (2021). (Source: GaBi 8.0 database).

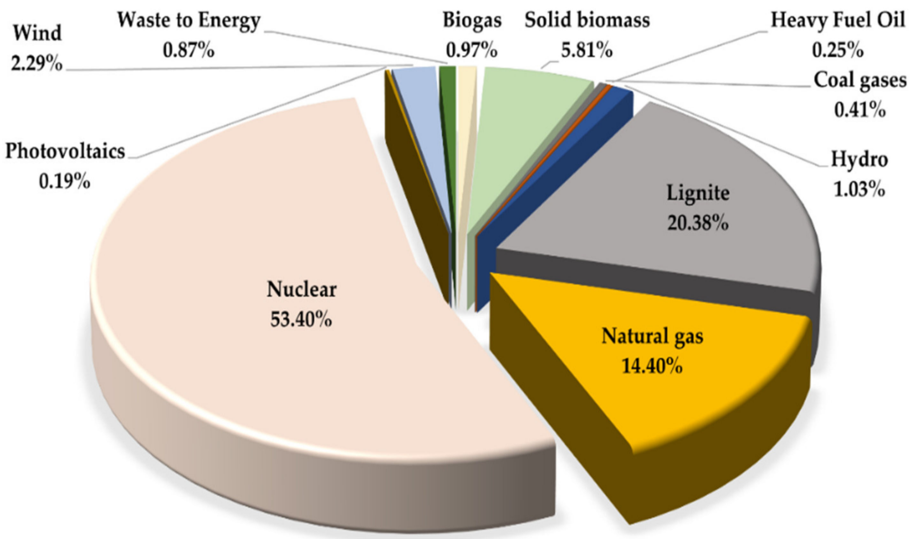

Figure 6. Electricity mix for Hungary (2021). (Source: GaBi 8.0 database).

3.3. Radioactive Waste and Spent Fuel Management Policy

The policies of RW and SNF management are of great national interest; these policies vary considerably among European Union (EU) members. Some EU members have re-examined their waste management options; others consider SNF as waste material; and still, others view SNF as a resource from which they hope to extract fissile material. Some countries still do not have a well-defined policy for nuclear waste (NW) management despite EU encouragement to define RW and SNF policies as part of their Council Directive 2011/70/EURATOM implementation.

EU legislation currently faces some issues relating to the formation of regulatory and implementation bodies to assess the SNF and RW management. EU legislation defines the necessary elements for inclusion in the country's policies, and other related governance for proper SNF and RW management [23].

According to the EU legislation, RW and SNF should remain in its country of origin. To be sure that RW is safe, technically optimal, and cost-effectively managed, the country requires appropriate policies and strategies. By adopting Council Directive 2011/70/EURATOM, EU member states have approved ethical legal obligations to maintain high safety levels during NW and SNF management to protect future generations from an unnecessary economic burden.

On 19 July 2011, the Council of the European Union adopted the European Parliament and Council Direct Directive 2011/70/EURATOM [24]. It established a public framework for proper SNF and NW management and provided an internationally binding legal force for the chiefly endorsed requirements and principles.

The directives of radioactive waste and spent fuel management required fulfillment of the following conditions:

- Member states should have a national policy for the proper management of SNF and NW.
- Member states should develop and implement national programs for the proper management and safe decommissioning of SNF and NW, including those that originated within their territory.
- Member states should have a comprehensive and robust framework in place for the proper management and safe decommissioning of NW and SNF. They should establish a competent autonomous regulatory body and have adequate funds for the proper management and safe decommissioning of NW and SNF.
- Information on NW and SNF should be readily available to common citizens who are allowed to participate in discussions.
- Member states should conduct self-evaluations and call for international peer reviews on their framework, competent authorities, and/or national programs, at least once a decade (by August 2023).
- The European Union can export NW to other countries for decommissioning but only under strict conditions.

According to work published by Ewing [25], a typical national policy must include the following elements: well-defined safety and security objectives, arrangements necessary to manage SNF and NW resources, primary identification methods of SNF and NW management, policies for the export and import of NW, and provisions for public information and their participation. In addition, the policy should define national roles and responsibilities for SNF and RW management.

3.4. Waste Composition and Characterization

Selecting the most appropriate storage and transport system requires knowing the NW composition. It is also essential to evaluate equipment needs, determine the potential for recovering any additional resources, choose a suitable decommission method, design sustainable management programs, and conduct proper planning. This information will help (1) to determine the possible impact on nature and on society; (2) identify targets for source reduction and recycling programs; and (3) allow technical professionals to design proper waste decommissioning systems [22].

Several factors affect the composition of NW, which begins with the nuclear fuel in the reactor. After going through the reactor, different radioactive materials produce different forms of RW. The second factor involves the reactor operation duration [22]. The longer the material is in the reactor, the more likely it is to form unstable isotopes. Finally, the composition of the NW depends on how long the container was maintained outside the reactor.

After producing electricity, SNF withdrawn from the reactors is primarily labeled as SNF. It will be hot, highly radioactive, and handled and shielded remotely [26]. Furthermore, HLW is a type of NW produced after SNF recycling (e.g., waste formed by vitrification of liquid HLW).

HLWs are hazardous as they are highly radioactive and emit a substantial amount of radiation. For instance, the surface dose rate for a typical SNF assembly exceeds 10,000 rem/hour, even ten years after removal from a reactor; this dose rate far exceeds the fatal exposure dose rate of ~500 rems for humans. HLWs may enter the food chain if their isotopes seep into the groundwater or river water [22].

HLW is produced after uranium has been burned in a nuclear reactor. It contains uranium, fission products, plutonium, and other elements. HLW accounts for approximately 3% of the total quantity and 95% of the total radioactivity of the NW [22]. HLW is categorized as waste and separated from used fuel reprocessing.

3.5. Waste Generation and Waste Management

In 14 EU countries, nearly 30% of the electricity is produced by a total of 130 nuclear power plants [27,28]. NW is generated during each stage of electricity production from nuclear materials [29], including activities such as conversion, enrichment, fuel fabrication, plant operation, treatment of used fuel, and decommissioning. Another large contribution stems from NW generated during the mining and milling of uranium, which may be classified as RW [30].

During reactor operation, uranium and plutonium produce highly irradiated fissile materials, which are present in the SNF. HLW is chiefly SNF removed from the reactor after electricity production. It is also an NW produced during the SNF recycling (e.g., waste formed by vitrification of liquid HLW).

According to the IEA's central scenario [19], the share of the world's nuclear power plants in total electricity generation was 11% in 2021. The quantity of NW produced by the NPPs is approximately 97% of the NW produced and is classified as low- or intermediate-level nuclear waste (LLW or ILW, respectively). LLW represents approximately 90% of the total amount of RWs, but accounts for only 1% of the total radioactivity [31–33].

The decommissioning of NW is extremely difficult because of its composition, and managing such hazardous waste is the major disadvantage of nuclear energy use. Based on the Fundamental Safety Principles of IAEA, RW management and decommissioning should be conducted to protect human health and the environment without causing an excessive economic burden to future generations [34]. By the end of 2013, the projected total inventory of RW in the EU was 3,313,000 m^3, including 54,300 tHM of SNF (Table 5).

Table 5. Total volume of radioactive waste and spent fuel in 2013 [35].

	Waste Category				
	VLLW(m^3)	**LLW (m^3)**	**ILW (m^3)**	**HLW (m^3)**	**Spent Fuel (tHM)**
Total amount	516,000	2,453,000	338,000	6000	54,300

From the data presented in Table 5, RW comprised approximately 74.04% LLW, 15.58% very low-level waste (VLLW), 10.20% ILW, and 0.18% HLW. Of the total waste generated, ~70% has been disposed and ~30% remains in storage. According to the data, at the end of 2013, The EU stored approximately 98.5% of SNF with the remaining 1.5% stored elsewhere pending recycling, with the expectation of a return to the EU after 2017.

3.6. Reprocessing of the SNF and Recycling of Uranium and Plutonium

After extracting SNF from the reactor, the next step is cooling in the reactor pools for an adequate cool-down period and required for each nuclear fuel cycle strategy. Then, SNF is removed from the pool, shipped in casks to the reprocessing plant, or transported for long-term storage.

Nuclear reprocessing is a series of chemical reactions from which fission products and unused plutonium and uranium are separated from SNF. Plutonium and uranium in spent fuel can be recovered through reprocessing. Plutonium can then be used in the production of mixed oxide (MOX) nuclear fuel to replace fresh uranium oxide fuel [32]. One-time recycling of plutonium in the form of MOX fuel will increase the energy from the original uranium by about 12%, and if uranium is also recycled, it will be about 22%. In the case of nuclear energy, it is important and essential that in most cases it can be recycled instead of disposing of the prepared nuclear fuel once and then disposing of it as waste, thus closing the fuel cycle. The current way to do this is to remove plutonium and use mixed oxide (MOX) fuel mixed with depleted uranium. Based on the data reported in [36] as of December 2018, approximately 7% of the world's operating nuclear plants are licensed to use MOX fuel.

Uranium naturally contains a greater fraction of U-238 and a small fraction of U-235 isotopes. All isotopes of uranium are radioactive. SNF still contains a very small fraction of the original U-235, some plutonium isotopes, and mostly U-238. Estimates suggest that SNF contains approximately 96% of the initial quantity of uranium and more than 50% of the initial content of nuclear energy (omitting U-238). Therefore, reprocessing would decrease the amount of HLW and yield fissile materials [34].

The highly radioactive isotopes present in the SNF will be lost in the absence of reprocessing the used reactor fuel. Failure to reprocess SNF results in its processing as HLW and direct disposal. However, because of the presence of uranium (and plutonium), many countries are reluctant to do things this way.

Used fuel contains plutonium, so reprocessing SNF produces a significant amount of plutonium, used to prepare fresh fuel. Approximately 25–30% of the energy from the SNF can be extracted due to the uranium present. This extraction step dramatically drops (~85%) the amount of HLW [36]. The HLW remaining after reprocessing contains significantly less radioactivity—decaying at a similar rate as the original ore (within 9000 years vs. 300,000 years for un-reprocessed HLW). Plutonium separation for recycling as MOX is more economical when the prices of uranium are high. The relative merit of MOX is that it decreases the amount of SNF.

The primary aims of recycling SNF are to convert long-lived radionuclides to shorter-lived or stable nuclides and efficiently use the SNF uranium. This requires the extraction of the nonreusable SNF residues that it contains. Plutonium recovery from SNF occurs by plutonium and uranium recovery by extraction (PUREX). Currently, PUREX is the standard method of extracting plutonium and uranium [37]. Separation typically generates actinides, and activation unstable, fission, and radioactive products. PUREX requires special facilities for processing SNF to convert it into a final suitable form for decommissioning [38]. Liquid HLW is vitrified after SNF reprocessing by mixing with melted vitrified glass material at high temperatures, which incorporates the wastes into the structure of the glass [37]. It is also vitrified into borosilicate (Pyrex) glass, sealed in heavy stainless-steel cylinders approximately 1.3 m high, and stored for eventual deep underground disposal. In addition, solid waste containing small amounts of long-lived substances (e.g., metal cladding on the fuel rods) also forms, which requires containment in a suitable manner for final decommissioning [39].

Reprocessing with reuse transforms SNF into high-level vitrified waste, MOX fuel with appropriate fissile content for reuse, and other RW. The extracted plutonium can produce MOX for use in the light water reactor (LWR). Reprocessed uranium is either mixed with plutonium (in a MOX fuel fabrication) or enriched to produce new uranium fuel [40]. Figure 7 presents the reprocessing with reuse of uranium and plutonium.

MOX contributes very little to the supply of nuclear reactors worldwide. Currently, plutonium does not undergo multiple recycling cycles (mono recycling). In some countries, SNF undergoes reprocessing and reuse as a recyclable fuel; in other countries, SNF just undergoes disposal as hazardous waste. Nevertheless, technological difficulties encountered by countries and industries to recycle waste by radionuclide separation and residue vitrification and public opposition force a large majority of states to temporarily store their SNF instead of reprocessing or disposing of it. Therefore, the SNF storage volume gets larger, and the storage period gets longer. In addition, MOX waste is more difficult to handle and shows higher temperatures than uranium waste, which limits the use of MOX in NPPs. MOX fuel supplies nearly 5% of the new nuclear fuel used currently. According to [41], only France India, Russia, and Japan have regulations for self SNF reprocessing (Table 6).

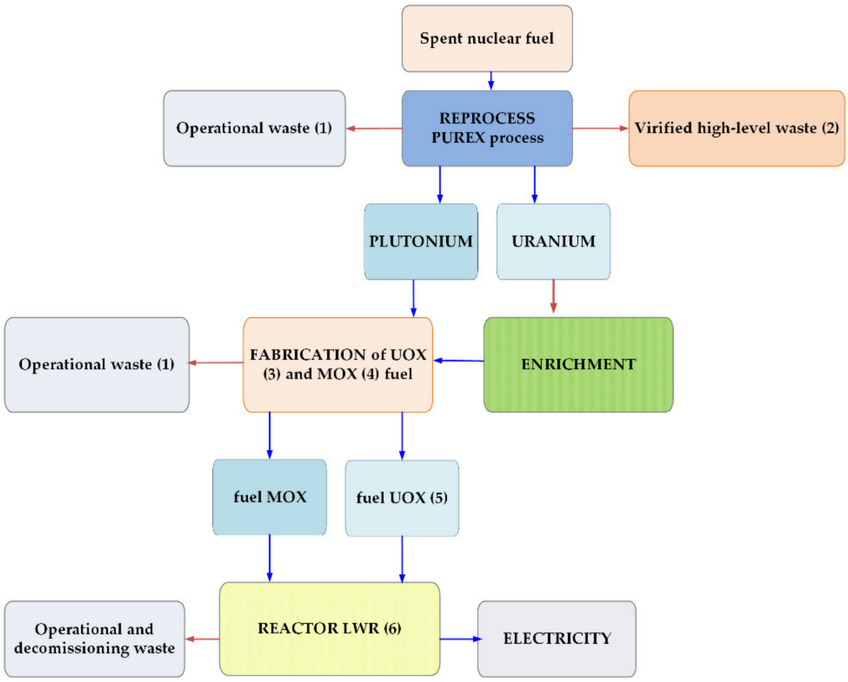

Figure 7. Reprocessing with reuse of uranium and plutonium. (**1**) Operational waste; (**2**) virified high-level waste; (**3**) uranium dioxide (UOX) fuel; (**4**) metal oxide (MOX) fuel; (**5**) fuel made of uranium dioxide; (**6**) light water reactor (LWR).

Table 6. Global MOX fuel fabrication capacity (t/year).

Country	Capacity
France	195
India	50
Russia	60
Japan	10

3.7. Deep Geologic Repository

Both sustainable developments of nuclear energy and preservation of our environment are achievable via safe decommissioning of SNF and HLW, despite the difficulty of that task for most countries that produce nuclear energy. Worldwide, many countries believe that deep SNF and HLW burial in a geological repository (DGR) is the most feasible and safe option, with plans to build one for disposal of SNF or vitrified HLW [42].

Many countries have tested different types of engineered barrier systems and geologic media for NW decommissioning. One of the proposed decommissioning techniques for HLW is a direct burial in DGRs. Such repositories should have room to house the HLW that has accumulated since the dawn of the nuclear era [43].

DGRs isolate NW permanently from humans and their environment. The safety of the repositories depends primarily on the combined effect of depth, natural barrier comprising rocks, the environment at the depth of the repository, and the effectiveness of the man-made engineered barrier that contains the NW. Selecting an appropriate DGR includes simultaneous consideration of the specific form of disposed of NW, the engineered seals, packaging in which the NW resides, and the underground geology. These factors all provide a high level of long-term NW isolation without future maintenance. Thus, many countries are trying to identify a stable geologic location where they can excavate a tunnel or drill a shaft below the earth's surface to excavate vaults and/or rooms for safe disposal of HLW [44].

Fundamentally, disposal of SNF and HLW involves a container that isolates the NW from the decommissioning environment until the radioactivity of the fission product drops to a safe level [45]. These containers are placed in a building where fixed concrete storage compartments are built. The surrounding concrete structure and the building provide shielding and protection against mechanical damage caused due to radiation [46].

Designing RW containers must consider standards established by authorities and international organizations and tested, reliable container materials. The technology of dry storage in metal and concrete containers has been developed by many groups. A previous study provides an overview of current repositories and designs of engineered barrier systems for selected HLW and SNF decommissioning from European countries; they provide a special reference to the key metallic waste containers and the process of corrosion [47]. Yin et al. [48] conducted a global study on the packaging designs and materials intended for radioactive NW decommissioning with a particular emphasis on the behavior of alloy C-22 in aging and corrosion. C-22 showed excellent corrosion resistance when used in a DGR. Duquette et al. [49] discussed the corrosion related to HLW decommissioning in the Yucca Mountain repository. Another study focused on metal containers intended for the decommissioning of solid RW [50].

Alloy types and their thicknesses are important factors to consider for corrosion allowance, conducted based on knowing the type and rate of corrosion as a function of time and temperature. Kursten et al. [51] reported a method to create a robust estimation of the Belgian Supercontainer, designed for the final underground decommissioning of vitrified HLW and SNF in Belgium. The Supercontainer consists of a carbon steel overpack, which contains vitrified HLW canisters or SNF assemblies. These assemblies are enclosed by an impenetrable concrete buffer. A stainless-steel envelope encloses this buffer; however, this study only examined uniform corrosion such as pitting, crevice, and stress corrosion.

Marsh and Taylor [52] assessed the use of carbon steel containers for the decommissioning of HLW. They focused on studying the use of carbon steel in a granite-rich environment and estimated the corrosion allowance required to achieve a container lifespan of 1000 years. Their results suggested that a carbon steel container of 216 thickness should suffice to prevent general and/or localized corrosion.

Othman et al. [53] studied the structural design for a container intended for decommissioning of HLW. They used a fiber-reinforced ultra-high-performance concrete material. The size of the dry storage container was optimized based on maximizing the stiffness and minimizing production costs while designing the container to withstand stresses. This new design was evaluated for its integrity based on realistic accidental drop-impact events; those results showed that using fiber-reinforced ultrahigh-performance concrete decreased container weight by more than 60%. This will probably increase the waste weight capacity when we consider gross weight restrictions. The new container integrity results showed less damage and disruption than the existing high-strength concrete or steel liner design. Containers with steel liner designs suffered significant damage aligned between the lid and the container body, which could cause the container to open. However, using fiber-reinforced ultra-high-performance concrete, the lid suffered less stress and damage at the body interface.

DGR burial is the primary option for SNF or HLW decommissioning worldwide. Based on the natural conditions existing in different countries, various geological settings have been evaluated for the safe decommissioning of NW. In China, Wang et al. [54] studied the progress of geologic decommissioning of HLW from 1985–2004. China wanted to build an HLW repository by the mid-21st century and wanted to dispose of vitrified and transuranic waste and small amounts of SNF. They proposed a DGR design to have a shaft-tunnel-silo model hosted by granite in the saturated zone.

At the end of 2012, the Finnish nuclear waste management company (Posiva), submitted an application to the government for a construction license of a disposal facility for spent fuel from the Loviisa and Olkiluoto nuclear power stations. Next, in 2018, Posiva announced the start of excavation on their deep geologic nuclear waste repository for their spent nuclear fuel at ONKALO. The repository will be the first in the world to start the final disposal of spent nuclear fuel. Operation of the repository is expected to begin in 2023.

Disposal in any repository in Finland will be based on the multi-barrier KBS-3 system developed by the Swedish Nuclear Fuel and Waste Management Company (SKB). Encapsulation will involve putting 12 fuel assemblies into a boron steel canister and enclosing this in a copper capsule. Each capsule will be placed in its own hole in the repository and backfilled with bentonite clay. The spent fuel will be retrievable at every stage of the disposal process. The idea is to encase the waste in corrosion-resistant copper canisters. These will be further encapsulated in a layer of water-absorbing clay. The setup will be buried in an underground tunnel [55].

France plans to construct the Centre Industriel de Stockage Géologique (Cigéo) repository—an underground system of disposal tunnels—in a natural layer of clay near Bure, to the east of Paris in the Meuse/Haute Marne area. In 2018, the French regulator, Autorité de Sûreté Nucléaire (ASN), issued a positive opinion on the safety options for the country's planned deep geological repository for the disposal of high level and intermediate level RW.

Cigeo is a deep geological disposal facility for radioactive waste to be built in France. It will serve for disposal of highly radioactive long-lived waste produced by France's current fleet of nuclear facilities, until they are dismantled, as well as from reprocessing of spent fuel from nuclear power plants.

Cigeo will consist of an underground area (for waste disposal) and surface facilities spread over two areas, as well as links between the surface and the underground. Waste disposal will take place for over 100 years and the facility will be expanded as space is needed [56].

After 40 years of study and preparation, a landmark decision has now been reached to build a geological repository for nuclear waste in Sweden. SKB, the Swedish Nuclear Fuel and Waste Management Company, is responsible for a system of facilities used to handle all waste from the Swedish nuclear power plants. These facilities include a central interim storage facility for spent nuclear fuel (Clab) near Oskarshamn, and a final repository for short-lived radioactive waste (SFR) in Forsmark. The reason to select the site in Forsmark, is that the granitic bedrock contains a relatively small number of fractures [57].

Based on the effective dose from the Recommendations of the International Commission on Radiological Protection 2007, reference levels were calculated for occupational exposure to radiation inside a representative DGR for HLW [58]. The representative DGR had a horizontal emplacement drift in rock salt. A typical HLW inventory is defined as a mixture that contains spent MOX and spent uranium oxide fuel. For an adequate estimation of the effective dose, the dose conversion coefficients for the anterior-to-posterior or the rotational geometries can be used based on the body orientation of the worker in the rock salt emplacement drift.

For decommissioning NW in a DGR, safety is an extremely important consideration. This requires identifying and evaluating factors that might affect the long-term case integrity in a DGR. It is also important to account for natural processes that might affect the long-term safety of the DGR [59]. McEvoy et al. [60] highlighted difficulties in developing a deep geological decommissioning program in the UK. They reviewed the natural changes that might affect the siting and design of a DGR.

Some research in the NW field sought to develop technology for the geological decommissioning of NW. Zhang et al. [61] selected a shaft and three intersecting tunnels at 560 m as the typical structure for an underground research laboratory. Their results showed that the minimum reliability index occurs at the intersection where the tunnels and shaft meet, which suggested the weakest parts of the structure were the intersecting corners. However, most of the reliability indices of the structure were above 4.2, which suggested the structure was safe after excavation. The design efficiency of a decommissioning system for SNFs must consider the decay heat of SNF because it is the major factor that affects the decommissioning area. Korean research suggested the decommissioning system design need not be overly conservative; the authors recommend achieving a repository footprint decreased by approximately 50%, achieved by accounting for the respective irradiation and cooling profile of the SNF [62].

3.8. Life Cycle Assessment Results

According to the research works of Szita [63], one requirement for sustainable life cycle management is an understanding of the lifecycle stages. If system boundaries are well-defined, we can apply life cycle inventory analysis and life cycle impact assessment (LCIA) with the help of LCA software. The results are important when declaring the abiotic depletion potential for non-fossil resources (ADP elements, ADPE) and for fossil resources (ADP fossil fuels, ADPF) for the EPD documentation. In accordance with the basic structure of the life cycle impact assessment, the impact category indicator result for abiotic depletion is calculated by reproducing Life Cycle Inventory (LCI) results and extractions of fossil fuels and elements by characterization factors. Uranium is accounted for in ADP for elements and is not listed as a fossil fuel. Fossil fuels are interchangeable during production, while uranium is not. Guinée and Heijungs [64] based the characterization model of ADP on physical data of reserves and yearly deaccumulation. Vadenbo et al. [65] proposed focusing on borrowing and dissipative supply use in impact assessments of abiotic resources. The life cycle assessment of the investigated production system was carried out by applying GaBi 8.0 software. The production stage of PET involved PET granule inputs, sodium hydroxide (caustic soda mix, 100%), and EU water as well as the necessary electric power and thermal energy, which may have environmental impacts. The raw materials for manufacturing PET granules assume 4 kg of PET granules forms 4 kg of PET product. The raw material distributions from the extraction sites to the production point were included during production and included relevant transport processes. The PET granules are a technology mix from Germany (PET via DMT). To compare the environmental loads caused by different energy mixes from different countries, we simulated a more common manufacturing process. PET bottles were produced from PET granules by considering the electricity mix for each country as an input stream during the construction of the LCA plan. For this production phase, the updated data was obtained from the GaBi 2021 professional database. The raw material backgrounds and excipients were also considered during analyses of the technological processes. These data represent the period 2020–2023. Life cycle assessment values apply to 4 kg of PET product in the non-shipped production phase. Bałdowska-Witos et al. [66] have reported several LCA analyses previously to produce PET bottles. An LCA-based complex model can be considered based on the viewpoints of a load of environment, energy efficiency, and economic efficiency [67].

Table 7 shows ADPE values using electricity mix and electricity only from nuclear input. We calculated these values based on a professional database in February 2021.

Table 7. ADPE values for different countries using electricity mix (scenario 1) and nuclear electricity of 100% (scenario 2) inputs at the production stage (with professional database 2021 of GaBi 8.0 software).

Country	Distribution of Nuclear Energy (2021) %	ADPE $\times 10^{-3}$ kg Sb eq. (Scenario 1)	ADPE $\times 10^{-5}$ kg Sb eq. (Scenario 2)
Bulgaria	34.80	4.99	10.1
Czech Republic	35.30	5.08	9.67
Finland	34.80	4.87	8.74
France	77.60	4.98	8.80
Hungary	53.40	4.98	9.71
Slovakia	56.80	5.01	9.84
Slovenia	36.50	5.00	9.63
Sweden	42.20	4.89	8.39
Switzerland	38.40	5.12	9.53
Ukraine	54.86	4.98	9.72
Belgium	46.60	5.13	8.73

As an example, Figure 8 presents the normalized and weighted values for the ADPE of input-output material flows and energy sources with help of the CML 2001/2016 LCIA method during PET product production in Slovenia. Three calculations of ADP (elements) from CML are integrated into GaBi software: (1) the baseline version based on ultimate reserve (i.e., the total mineral content in the earth crust), (2) the reserve base which includes what is considered available in significant concentrations in the earth, and (3) the economic reserve based on what is evaluated as being economically feasible to extract [16].

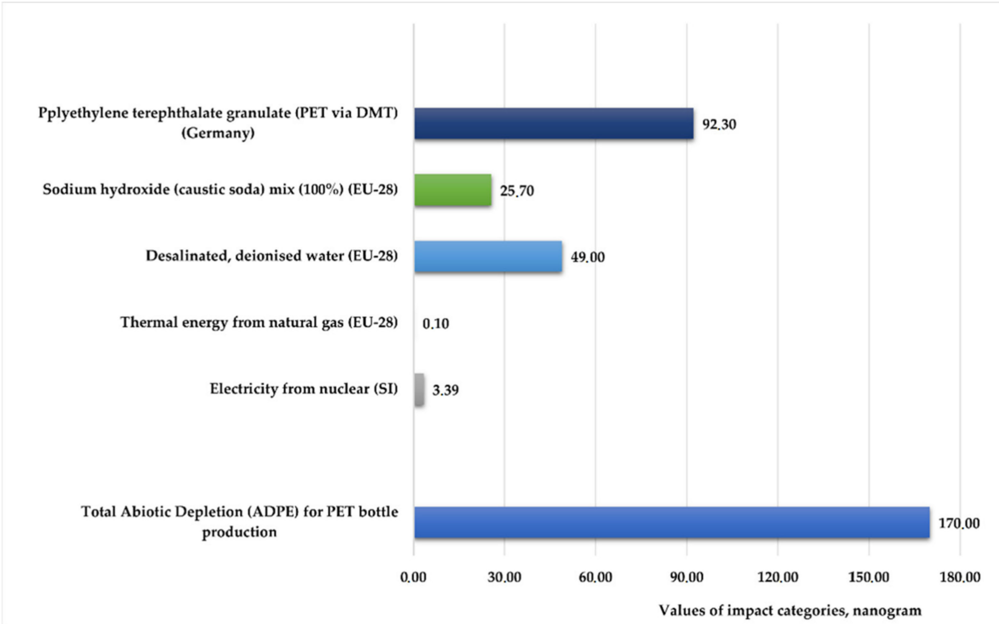

Figure 8. Abiotic depletion values for elements (ADPE) during PET bottle production. (Functional unit: 4 kg PET product. Normalization reference: CML 2016, EU 25 + 3, year 2000, excl. biogenic carbon. Weighting method: thinkstep LCIA Survey 2012, Europe, CML 2016, excl. biogenic carbon.).

Modeling using GaBi software showed the abiotic depletion for elements is only 0.05% compared to other environmental impact categories. Abiotic depletion values for water and caustic soda were higher. As shown in Table 7, comparing the energy mix (Scenario 1) with only nuclear energy (Scenario 2) and introducing it as an energy input into PET bottle manufacturing, Scenario 2 yielded lower ADPE values by two orders of magnitude. The improved practice of LCAs could improve new production strategies aimed at prolonging the lifecycle of packaging PET [68]. Therefore, we tried to present a practical example of a manufacturing process for the different energy inputs whose LCA analysis results may be useful in the future.

4. Discussion

Climate and energy frameworks target reductions of greenhouse gas emissions by at least 40% by 2030. The European Commission has published a new document calling for the EU to achieve net-zero greenhouse gas emissions by 2050, with NPPs playing a major role in this effort [69]. Therefore, NW generation should increase during this century with a concomitant increase in nuclear energy consumption. Thus, implementing a recycling economic policy strategy that involves recycling waste instead of utilizing primary resources merits immediate attention. NW is radioactive and requires careful management and decommissioning. In some countries, SNF gets recycled and reused while other countries simply disposed of SNF as hazardous waste. However, technological difficulties and public opposition force many countries to store their SNF temporarily instead of recycling or disposing of it. The accumulation and storage time of SNF increases by the day. SNF still contains 90% usable fuel. The sensible option is to reprocess and extract the unused uranium and plutonium for recycling into fresh uranium fuel. Currently, most countries that operate nuclear power plants intend to dispose of their SNF in DGRs without further reprocessing. This leads to an increase in the amount of HLW for storage and decommissioning. The management of SNF and NW requires a safe, secure, and permanent decommissioning technique [70]. Two such methods involve the development of a DGR and a nuclear fuel reprocessing plant.

According to the waste hierarchy, the most efficient NW management strategy minimizes waste generation at the source (while exploiting NPPs). Ideally, this should be achieved during the NPPs design stage by selecting appropriate technologies and designs. Radiation scientists, geologists, and engineers have developed and implemented most of the necessary technologies required for the safe and final decommissioning of NW. Worldwide, a deep geological repository (safe underground storage) has emerged as the best practice for the final decommission of SNF and HLW. Presently, plutonium does not undergo multiple recycling cycles (mono recycling). Similarly, the use of reprocessed uranium is limited by the necessity of over-enrichment (of U-235) to compensate for the presence of U-236 formed by neutron capture, as the latter is a neutron poison. Furthermore, the handling of reprocessed uranium requires protection against gamma emission due to Thallium-208, which is a decay product of U-232. Market forces guide the use of reprocessed uranium and separative work units (SWU). Despite the isotopic degradation of plutonium with the burn-up, there is increasing interest in recycling plutonium (~10 times) in thermal neutron reactors, but this will not dramatically change the lack of sustainability of nuclear energy based on thermal neutron reactors. Multiple recycling cycles in thermal neutron reactors also raise the question of whether minor actinides would accumulate in the final waste and to what extent.

Within this research work, first, uranium resources and nuclear energy production were examined with help of different tables and energy mix diagrams. In addition, a life cycle assessment was accomplished for the production process of PET bottles with nuclear energy inputs. The objective of the experimental research work was the determination of the abiotic resource depletion elements. This research work applied the following main methods: literature research on the uranium production and nuclear power plants, the primary energy sources of the basic production process, the SNF, uranium and plutonium reprocessing, and the life cycle assessment method. In recent years, life cycle assessment methods have made it possible to develop a common and widely understood language to address assessment challenges [71]. Currently, the researcher's primary focus on aspects related to waste disposal process management is based on LCA, contrasting the environmental impacts of different waste treatment methods. There are many research works [72,73] for the evaluation of complex LCA models for different production processes. In addition to its original function regarding the analysis of material products, the application of life cycle assessment can be extended for the manufacturing process (for example PET bottle manufacturing) with different energy flows. We, therefore, considered it important to examine and compare a basic production stage with the application of energy mix and only nuclear energy inputs separately.

According to LCA results, eleven countries produced primary energies of 3.41–3.6 $\times$ 10^5 MJ from non-renewable resources and 2.7–3.15 $\times$ 10^4 MJ from nuclear electricity. The average total value of ADPE for production was 0.00484 kg Sb equivalent. By comparing the energy mix input with only nuclear energy input into PET bottle production, a nuclear energy input of 100% resulted in a much smaller ADPE. By measuring long-term effects, the resources and emission findings can illustrate weak points and possibilities in NW management. It is worth examining how each NW individually impacts the environmental load of future landfills.

Basically, there is very poor professional literature available on LCA for nuclear powers. The research results can be used to design and compare manufacturing processes involving nuclear electricity input in different countries. This research work is relevant because the determination of abiotic resources is important in a life cycle assessment.

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Abbreviations

ADP	Abiotic Depletion Potential
ADPE	Abiotic Depletion Potential for Elements
ADPF	Abiotic Depletion Potential for Fossils
BWR	Boiling Water
DGR	Deep Geological repository
EPD	Environmental Product Declaration
FU	Functional Unit
HLW	High-level Nuclear Waste
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
ILW	Intermediate-level Nuclear Waste
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LLW	Low-level Nuclear Waste
MOX	Mixed Oxide
NPP	Nuclear Power Plant
NW	Nuclear Waste
PBs	Planetary Boundaries
PEF	Product Environmental Footprint
PET	Polyethylene Terephthalate
PRIS	Power Reactor Information System
PUREX	Plutonium and Uranium Recovery by Extraction
PWR	Pressurized Water
RAR	Reasonably Assured Resources
RW	Radioactive Waste
SDG	Sustainable Development Goal
SFR	Short-Lived Radioactive Waste
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	Spent Nuclear Fuel
UOX	Uranium Dioxide

References

1. Gawlik, L.; Mokrzycki, E. Fossil fuels in the national power sector—Problems and challenges. *Polytika Energetyczna—Energy Policy J.* **2017**, *20*, 5–25.
2. *World Energy Resources*; World Energy Council: London, UK, 2016; p. 4. ISBN 9780946121588.
3. Grimes, R.W.; Nuttall, W.J. Generating the option of a two-stage nuclear renaissance. *Science* **2010**, *329*, 799–803. [CrossRef] [PubMed]
4. *The World Energy Issues Monitor 2022*; World Energy Council: London, UK, 2022; Available online: https://www.worldenergy.org/publications/entry/world-energy-issues-monitor-2022 (accessed on 26 January 2022).
5. Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Minx, J.C.; Farahani, E.; Kadner, S.; Seyboth, K.; Adler, A.; Baum, I.; Brunner, S.; et al. *Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Inter-governmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2014; pp. 1–33.

6. Yano, K.H.; Mao, K.S.; Wharry, J.P.; Porterfield, D.M. Investing in a permanent and sustainable nuclear waste disposal solution. *Prog. Nucl. Energy* **2018**, *108*, 474–479. [CrossRef]
7. Zhang, Q.; Huang, Y.; Sand, W.; Wang, X. Effects of deep geological environments for nuclear waste disposal on the hydrogen entry into titanium. *Int. J. Hydrogen Energy* **2019**, *44*, 12200–12214. [CrossRef]
8. Eerkens, J.W. *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis*; Springer: Dordrecht, The Netherland, 2006; 160p, ISBN 1402049307.
9. Lukens, W.W.; Saslow, S.A. Aqueous synthesis of technetium-doped titanium dioxide by direct oxidation of titanium powder, a precursor for ceramic nuclear waste forms. *Chem. Mater.* **2017**, *29*, 10369–10376. [CrossRef]
10. Choppin, G.; Liljenzin, J.-O.; Rydberg, J. *Radiochemistry and Nuclear Chemistry, Chapter 20—Nuclear Power Reactors*, 3rd ed.; Butterworth-Heinemann: Oxford, UK, 2001; pp. 560–582. ISBN 9780080515663.
11. Wallenius, J. Maximum efficiency nuclear waste transmutation. *Ann. Nucl. Energy* **2019**, *125*, 74–79. [CrossRef]
12. European Commission. *Annual Report 2018, Euratom Supply Energy*; Energy Series; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-76-03394-3.
13. Borodin, Y.V.; Aliferova, T.E.; Ncube, A. Waste management through life cycle assessment of products. *IOP Conf. Ser. Mater. Sci. Eng.* **2015**, *81*, 012085. [CrossRef]
14. European Commission. *Report on Critical Raw Materials for the EU*; European Commission: Brussels, Belgium, 2014; Available online: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm (accessed on 29 February 2016).
15. European Commission. Recommendations for Life Cycle Impact Assessment in the European context—Based on Existing Environmental Impact Assessment Models and Factors. In *ILCD Handbook*; European Commission, Joint Research Centre, Institute for Environment and Sustainability: Ispra, Italy, 2011; Available online: http://publications.jrc.ec.europa.eu/repository/handle/JRC61049 (accessed on 29 February 2016).
16. Sphera GaBi. *GaBi Databases & Modeling Principles 2022*; Sphera: Chicago, IL, USA, 24 February 2022.
17. Sanyé-Mengual, E.; Sala, S. Life Cycle Assessment support to environmental ambitions of EU policies and the Sustainable Development Goals. *Integr. Environ. Assess. Manag.* **2022**, 1–12. [CrossRef]
18. Uranium 2020: Resources, Production and Demand. In *A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency*; NEA No. 7551; OECD: Paris, France, 2020.
19. Database Documentation. IEA World Energy Balances, 2021 Edition. Available online: https://www.iea.org/data-and-statistics/data-products?filter=balances%2Fstatistics (accessed on 1 May 2022).
20. Power Reactor Information System. Available online: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx (accessed on 12 May 2022).
21. Operational & Long-Term Shutdown Reactors. Available online: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx (accessed on 2 February 2020).
22. World Nuclear Association, Radioactive Waste Management. Available online: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx (accessed on 1 January 2022).
23. IAEA. *International Atomic Energy Agency, Status and Trends in Spent Fuel and Radioactive Waste Management*; IAEA Nuclear Energy Series, No. NW-T-1.14; IAEA: Vienna, Austria, 2018.
24. Council Directive 2011/70/EURATOM establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. *Official Journal of the European Union. 2.8.* 2011. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070&from=DA (accessed on 1 January 2022).
25. Ewing, R.C. Nuclear Waste Forms for Actinides. *Proc Nat. Acad. Sci. USA* **1999**, *96*, 3432–3439. [CrossRef]
26. U.S. NRC. Backgrounder on Radioactive Waste. Available online: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html (accessed on 23 July 2019).
27. OECD. *Waste Management and the Circular Economy in Selected OECD Countries: Evidence from Environmental Performance Reviews*; OECD Publishing: Paris, France, 2019. [CrossRef]
28. European Commission. 2019. Available online: https://energy.ec.europa.eu/topics/nuclear-energy_en (accessed on 13 November 2019).
29. European Commission. *Commission Staff Worming Document, Inventory of Radioactive Waste and Spent Fuel Present in the Community's Territory and the Prospects*; European Commission: Brussels, Belgium, 2017.
30. World Nuclear Association. What Are Nuclear Wastes and How Are They Managed? Available online: https://www.world-nuclear.org/nuclear-basics/what-are-nuclear-wastes.aspx (accessed on 1 October 2018).
31. IAEA. *International Atomic Energy Agency, Policies and Strategies for Radioactive Waste Management*; IAEA Nuclear Energy Series, No. NW-G-1.1; IAEA: Vienna, Austria, 2019.
32. Orton, C.R.; Fraga, C.G.; Christensen, R.C.; Schwantes, J.M. Proof of concept simulations of the Multi-Isotope Process monitor: An online, nondestructive, near-real-time safeguards monitor for nuclear fuel reprocessing facilities. *Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2011**, *629*, 209–219. [CrossRef]
33. Zohuri, B.; McDaniel, P. *Thermodynamics in Nuclear Power Plan System*, 2nd ed.; Springer: New York, NY, USA, 2018; p. 522.
34. IAEA. *Safety Standards for Protecting People and the Environment. Fundamental Safety Principles. 2006. International Atomic Energy Agency, Policies and Strategies for Radioactive Waste Management*; IAEA Safety Standards Series, No. SF-1; IAEA: Vienna, Austria,

2006; Available online: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1273_web.pdf (accessed on 7 November 2006).
35. European Parliament. *Report from the Commission to the Council and the European Parliament on Progress of Implementation of Council Directive 2011/70/EURATOM and an Inventory of Radioactive Waste and Spent Fuel Present in the Community's Territory and the Future Prospects*; Second Report, COM(2019) 632 Final; European Parliament: Brussels, Belgium, 17 December 2019.
36. Processing of Used Nuclear Fuel. Available online: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx (accessed on 1 December 2020).
37. Salama, A.; El Amin, M.F.; Sun, S. Numerical investigation of high-level nuclear waste disposal in deep anisotropic geologic repositories. *Prog. Nucl. Energy* **2015**, *85*, 747–755. [CrossRef]
38. New IPFM Report: Plutonium Separation in Nuclear Power Programs Status, Problems, and Prospects of Civilian Reprocessing Around the World. Available online: http://fissilematerials.org/blog/2015/07/new_ipfm_report_plutonium.html (accessed on 17 July 2015).
39. Bolgren, D.; Menees, J. Nuclear Fuel Reprocessing. CHE 4253. Bagajewicz, M., Ed.; Available online: https://www.ou.edu/class/che-design/a-design/projects-2007/Nuclear%20Reprocessing.pdf (accessed on 30 April 2007).
40. Andrews, A. Nuclear Fuel Reprocessing: U.S. Policy. CRS Report For Congress. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiP28nyxqL4AhXWAN4KHT99DRYQFnoECAUQAQ&url=https%3A%2F%2Fcrsreports.congress.gov%2Fproduct%2Fpdf%2FRS%2FRS22542&usg=AOvVaw1-9xPukLnyHF1gRTDFH5Fh (accessed on 25 March 2011).
41. Uranium Maps and Statistics. Available online: https://www.wise-uranium.org/umaps.html?set=fmox (accessed on 17 August 2019).
42. Wang, J.; Chen, L.; Su, R.; Zhao, X. The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests. *J. Rock Mech. Geotech. Eng.* **2018**, *10*, 411–435. [CrossRef]
43. Jobmann, M.; Bebiolka, A.; Burlaka, V.; Herold, P.; Jahn, S.; Lommerzheim, A.; Maßmanna, J.; Meleshyn, A.; Mrugalla, S.; Reinhold, K.; et al. Safety assessment methodology for a German high-level waste repository in clay formation. *J. Rock Mech. Geotech. Eng.* **2017**, *9*, 856–876. [CrossRef]
44. Hooper, A.J. 5—Crystalline Geological Repository Systems: Characterisation, Site Surveying and Construction Technologies and Techniques. In *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste 2010*; Woodhead Publishing Series in Energy; Woodhead Publishing: Cambridge, UK, 2010; pp. 121–152.
45. Berlepsch, T.V. 6—Salt Repository Systems: Design Development Approach at the Example of the Gorleben Salt Dome. In *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste 2017*; Woodhead Publishing Series in Energy; Woodhead Publishing: Cambridge, UK, 2017; pp. 145–162.
46. Acar, B.B.; Zabunoğlu, O.H. Impact assessment of alternative back-end fuel cycles on geological disposal of resultant spent fuels and high level wastes. *Ann. Nucl. Energy* **2019**, *130*, 452–472. [CrossRef]
47. Bennett, D.G.; Gens, R. Overview of European concepts for high-level waste and spent fuel disposal with special reference waste container corrosion. *J. Nucl. Mater.* **2008**, *379*, 1–8. [CrossRef]
48. Yin, K.J.; Li, C.; Qiu, S.Y.; Luo, Q. Review on status of nuclear waste package materials. *Hedongli Gongcheng/Nuclear Power Eng.* **2007**, *28*, 76–80.
49. Duquette, D.J.; Latanision, R.M.; Di Bella, C.A.W.; Kirstein, B.E. Corrosion issues related to disposal of high-level nuclear waste in the yucca mountain repository-peer reviewers' perspective. *Corrosion* **2009**, *65*, 272–280. [CrossRef]
50. Crossland, I.G. 12—Development and Use of Metal Containers for the Disposal of Radioactive Wastes. In *Handbook of Advanced Ra-dioactive Waste Conditioning Technologies 2011*; Woodhead Publishing Series in Energy; Woodhead Publishing: Cambridge, UK, 2011; pp. 363–394.
51. Kursten, B.; Druyts, F. Methodology to make a robust estimation of the carbon steel overpack lifetime with respect to the Belgian Supercontainer design. *J. Nucl. Mater.* **2008**, *379*, 91–96. [CrossRef]
52. Marsh, G.P.; Taylor, K.J. An assessment of carbon steel containers for radioactive waste disposal. *Corros. Sci.* **1988**, *28*, 289–320. [CrossRef]
53. Othman, H.; Sabrah, T.; Marzouk, H. Conceptual design of ultra-high performance fiber reinforced concrete nuclear waste container. *Nucl. Eng. Technol.* **2019**, *51*, 588–599. [CrossRef]
54. Wang, J.; Xu, G.; Zheng, H.; Fan, X.; Wang, C.; Fan, Z. Geological disposal of high level radioactive waste in China: Progress during 1985–2004. *World Nucl. Geosci.* **2005**, *22*, 5–15.
55. Conca, J. Finland Breaks Ground On World's First Deep Geologic Nuclear Waste Repository. Available online: https://www.forbes.com/sites/jamesconca/2021/05/31/finland-breaks-ground-on-its-deep-geologic-nuclear-waste-repository/ (accessed on 31 May 2021).
56. World Nuclear News. French Regulator Approves Repository Safety Options. Available online: https://www.world-nuclear-news.org/WR-French-regulator-approves-repository-safety-options-1501184.html (accessed on 15 January 2018).
57. Kombrink, H. Swedish Government Approves Deep Geological Repository for Nuclear Waste. *Expronews*. Available online: https://expronews.com/resources/swedish-government-approves-deep-geological-repository-for-nuclear-waste (accessed on 28 January 2022).

58. Bo, P.; Saurí Suárez, H.; Becker, F. Reference level of the occupational radiation exposure in a deep geological disposal facility for high-level nuclear waste: A Monte Carlo study. *Ann. Nucl. Energy* **2017**, *110*, 258–264.
59. Stephens, M.B.; Follin, S.; Petersson, J.; Isaksson, H.; Juhlin, C.; Simeonov, A. Review of the deterministic modelling of deformation zones and fracture domains at the site proposed for a spent nuclear fuel repository, Sweden, and consequences of structural ani-sotropy. *Tectonophysics* **2015**, *653*, 68–94. [CrossRef]
60. McEvoy, F.M.; Schofield, D.I.; Shaw, R.P.; Norrisc, S. Tectonic and climatic considerations for deep geological disposal of radioactive waste: A UK perspective. *Sci. Total Environ.* **2016**, *571*, 507–521. [CrossRef]
61. Zhang, Y.; Zhang, Q.Y.; Duan, K.; Yu, G.Y.; Jiao, Y.Y. Reliability analysis of deep underground research laboratory in Beishan for geological disposal of high-level radioactive waste. *Comput. Geotech.* **2020**, *118*, 103328. [CrossRef]
62. Cho, D.K.; Jeong, J. Effectiveness of source term optimization for higher disposal density of spent fuels in a deep geological repository. *Ann. Nucl. Energy* **2014**, *71*, 125–129. [CrossRef]
63. Szita, K. The Application of Life Cycle Assessment in Circular Economy. *Hung. Agric. Eng.* **2017**, *31*, 5–9. [CrossRef]
64. Guinée, J.; Heijungs, R. A proposal for the definition of resource equivalency factors for use in product Life-Cycle Assessment. *Environ. Toxicol. Chem.* **1995**, *14*, 917–925. [CrossRef]
65. Vadenbo, C.; Rørbech, J.; Haupt, M.; Frischknecht, R. Abiotic resources: New impact assessment approaches in view of resource efficiency and resource criticality—55th Discussion Forum on Life Cycle Assessment, Zurich, Switzerland 11 April 2014. *Int. J. Life Cycle Assess.* **2014**, *19*, 1686–1692. [CrossRef]
66. Bałdowska-Witos, P.; Kruszelnicka, W.; Tomporowski, A. LCA analyzes were also performed for the production of PET bottle. Life cycle assessment of beverage bottles. *J. Phys. Conf. Ser.* **2020**, *1426*, 012038. [CrossRef]
67. Mannheim, V. Life Cycle Assessment Model of Plastic Products: Comparing Environmental Impacts for Different Scenarios in the Production Stage. *Polymers* **2021**, *13*, 777. [CrossRef]
68. Sazdovski, I.; Bala, A.; Fullana-i-Palmer, P. Linking LCA literature with circular economy value creation: A review on beverage packaging. *Sci. Total Environ.* **2021**, *771*, 145322. [CrossRef]
69. Busby, J.P.; Lee, J.R.; Kender, S.; Williamson, J.P.; Norris, S. Modelling the potential for permafrost development on a radioactive waste geological disposal facility in Great Britain. *Proc. Geol. Assoc.* **2015**, *126*, 664–674. [CrossRef]
70. Sanders, M.; Sanders, C. A world's dilemma 'upon which the sun never sets'—The nuclear waste management strategy (part III): Western European Nation States and the United States of America. *Prog. Nucl. Energy* **2016**, *90*, 69–97. [CrossRef]
71. Szamosi, Z.; Bodnár, I.; Szepesi, L.G.; Rosas-Casals, M.; Berényi, L. Improved environmental impact in the architecture industry: LCA analysis of an alternative masonry element. *Renew. Energy* **2020**, *147*, 1718–1727. [CrossRef]
72. Civancik-Uslu, D.; Puig, R.; Ferrer, L.; Fullana-i-Palmer, P. Influence of end-of-life allocation, credits and other methodological issues in LCA of compounds: An in-company circular economy case study on packaging. *J. Clean. Prod.* **2019**, *212*, 925–940. [CrossRef]
73. Civancik-Uslu, D.; Ferrer, L.; Puig, R.; Fullana-i-Palmer, P. Are functional fillers improving environmental behavior of plastics? A review on LCA studies. *Sci. Total Environ.* **2018**, *626*, 927–940. [CrossRef]