MSc Program
Environmental Technology & International Affairs

Applying the concept of Circular Economy in the nuclear sector - An analysis based on two examples: resource extraction and nuclear decomisisoning

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Assoc.Prof.Dipl.-Ing.Dr.techn. Johann Fellner

Anastasia Lazykina, B.A.

01106134

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Affidavit

I, **ANASTASIA LAZYKINA, B.A.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "APPLYING THE CONCEPT OF CIRCULAR ECONOMY IN THE NUCLEAR SECTOR - AN ANALYSIS BASED ON TWO EXAMPLES: RESOURCE EXTRACTION AND NUCLEAR DECOMISISONING", 53 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

With every year, resource consumption in Europe and across the globe is increasing, alongside with the growing worldwide demand. Especially in areas that are sensitive from an ecological point, this development is adding additional pressure on the challenges that climate change, biodiversity loss and soil degradation are already causing. Solutions needs to be found and decisions need to be made in order to mitigate the ongoing damage to our environment. Additionally, consumption patterns need to change so that a more sustainable and efficient resource use can be achieved. Two potential solutions for the above-mentioned challenge could be the switch to an increasingly more circular economy, as well as the transition to non-fossil energy carriers. In early January 2022 the European Commission submitted a proposal to its Member States, which classifies nuclear as a sustainable investment. Since no CO2 emissions are produced during energy generation in a nuclear power plant, nuclear energy could support the EU target to become climate neutral by 2050. However, one has to keep in mind that a nuclear "renaissance" will not be possible without a sound and collaborative decommissioning industry.
This work will examine to which extent the concept of circular economy can be applied in the nuclear sector, based on two examples, the uranium resource extraction side, since mining processes are quite energy consuming and have several long lasting impacts on the environment ,as well as from the end of life site of the nuclear power fleet itself, due to the fact that in Europe alone it is planned to decommission a significant number of nuclear power plants, keeping in mind that most of the current nuclear power plants that will have to be decommissioned soon, were built where almost no consideration was given to sustainable or circular decommissioning. Difficulties and obstacles will be pointed out and possible solutions will be provided.

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1 Introduction

1.1 Problem Statement

With every year, resource consumption in Europe and across the globe is increasing, alongside the growing worldwide demand. Especially in areas that are sensitive from an ecological point, this development is adding additional pressure on the challenges that climate change, biodiversity loss and soil degradation are already causing.
Extraction of raw materials is a complex process and entails several stages such as exploration, development, extraction, closure and rehabilitation. Each of these phases has a different impact on the environment. *"The key factors in this regard are the impact on local ecosystems and biodiversity, impact on the water balance, the handling of mining wastes, energy consumption, and water, soil and air emissions. The nature and extent of each of these vary greatly depending on factors related to the following: raw materials that come into play, technology, policies and institutions, society and ecology."* (Umweltundesamt Deutschland, 2019)
Additionally, it is important to mention that the extraction and processing of raw material are energy intensive processes and therefore result in greenhouse gas emissions. Energy, water and land are all resources that are consumed in the process. Hence solutions need to be found and decisions need to be made in order to mitigate the damage that has already been caused. Additionally, consumption patterns have to be reconsidered, in order to achieve a more sustainable and efficient resource use. (Umweltbundesamt Deutschland, 2014)
Two potential solutions for the above-mentioned challenge could be the switch to an increasingly more circular economy, as well as the transition to non-fossil energy carriers.

1.1.1 The European Green deal, its mechanisms and legal framework

The European Green Deal is the new and main growth strategy of the European Union with the aim to transition the EU economy to a climate neutral one, with the main goal to achieve climate neutrality by 2050.
The funding of the green deal is described in the Green Deal investment plan, backed up by several funding mechanisms, accounting for around 1 trillion EUR.

Figure 1 below describes how the European Green Deal is laid out:

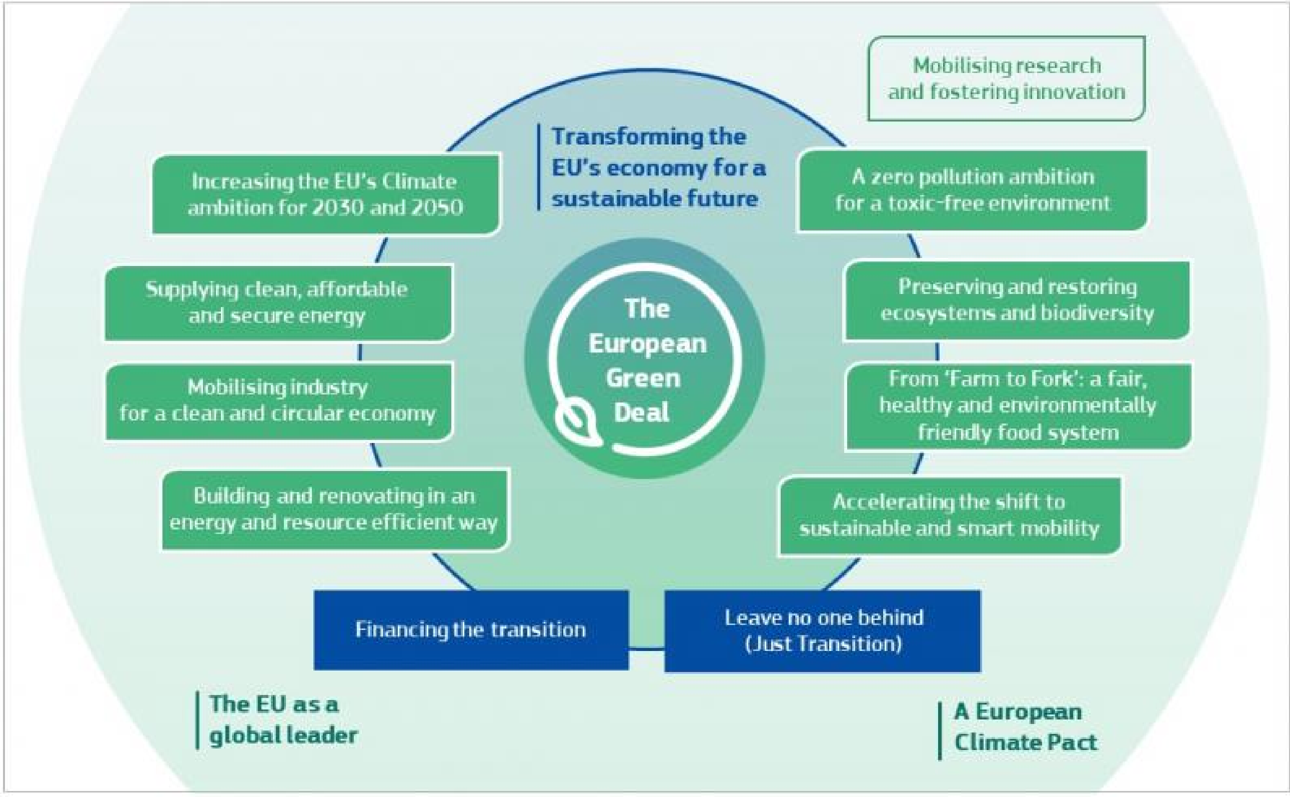

Figure 1: The European Green Deal (Eurostat, 2020)

The circular economy action plan, adopted in early 2020, is one of the main building blocks of the European green deal, as one can see in figure 1. It includes initiatives throughout the whole lifecycle of products. "Starting with the design of a product, promoting processes of circular economy, encouraging sustainable consumption" with. It consists of 35 actions along the entire life cycle of products to:

"

- *Make sustainable products the norm in the EU*
- *Empower consumers and public buyers*
- *Focus on key product value chains*
- *Ensure less waste*
- *Make circularity work for people, regions and cities*
- *Lead global efforts on circular economy*" (European Commission, 2022 a)

One of the key points listed above is ensuring that there is less waste. Here, the European Waste Policy, which will be described in more detail in chapter 2.2, plays an important role. The European Waste Policy is legally supported by the Waste Framework directive of the European Union and entails the Waste hierarchy, which is the foundation for the management of waste in the European Union and describes an order of preference for the management of waste. As it will be discussed later in chapter 2.2.1, the waste hierarchy has several similarities with the concept of circular economy, which will be of particular importance for my research.

1.1.3 EU Taxonomy

The European Commission submitted a proposal to its Member States early January 2022 to classify nuclear power as a sustainable investment (European Commission, EU Taxonomy, 2022 b) Combating climate change is one of the top priorities of the European Union, and therefore the EU has set a target to become climate neutral by 2050 in all economic sectors, which requires compensation of CO2 as well as other greenhouse gas emissions.

To achieve this goal, additionally to the already excising policy framework, *"several Green Deal Initiatives have been adopted. One of them is the EU Taxonomy regulation (EU 2020/852)."* (European Commission, EU Taxonomy, 2022 b) It serves as a system which helps to classify which investments are seen as environmentally sustainable *in relation to the European green deal*, setting out conditions as well as environmental objectives, that an economic activity has to fulfill in order to be qualified as environmentally sustainable.

To proper establish these definitions, a Technical Expert Group (TEG) on sustainable finance was established by the European Commission with the aim to: *"Develop recommendations for technical screening criteria for economic activities that can make a substantial contribution to the climate change mitigation or adaptation objectives, while avoiding significant harm to the four other environmental objectives of the Regulation:*

- *sustainable use and protection of water and marine resources;*
- *transition to a circular economy;*
- *pollution prevention control; and*
- *protection and restoration of biodiversity and ecosystems. "* (European Commission, EU Taxonomy, 2022 b)

In an assessment conducted in 2019 the technical expert group concluded that Nuclear Energy has near to zero greenhouse gas emission in the energy generation phase and therefore can serve for the objectives of climate change mitigation. However, a conclusion could not be reached regarding the matter on causing harm to other environmental objectives, especially in relation to the disposal of the high-level nuclear waste. As a result, at this stage, nuclear energy

was not included in the EU Taxonomy. However, the Joint Research Center (JRC) of the European Commission was tasked with the drafting of an assessment report in the "do no significant harm" (DNSH) aspects of nuclear energy, including the aspects that are related to the long-term management of high-level radioactive waste, as well as spent nuclear fuel.
In early January 2022 it was announced by the European Commission that Nuclear Energy can play a significant role when it comes to the goal related to decarbonization in the European Union. In the newly proposed Complementary delegated Act (CDA) three particular elements are proposed for the taxonomy:

- Demonstration units for advanced nuclear technologies
- The construction of new nuclear power plants using best available technologies
- Electricity generation from existing nuclear installations

Fossil gas activities are also stated in the CDA, however, compared to nuclear they are clearly marked as transitional (with the goal of being phased out as more green alternatives become available). *"The status of nuclear energy outlined in the proposed is more ambiguous. On the one hand the CDA notes that "evidence on the potential substantial contribution of nuclear energy to climate mitigation objectives was extensive and clear".* (European Commission, EU Taxonomy, 2022 b). The word transitional is not used in relation to nuclear energy at any point which seems to indicate that nuclear is recognized as making a significant contribution to mitigating climate change. However, complicating matters are that sunset clauses are included for new nuclear constructions and the long-term operation of existing plants. These must be authorized by competent authorities by 2045 and 2040, respectively. (European Commission, EU Taxonomy, 2022 b)

Additionally, the complementary Delegated Act is stating that there are certain outlines that nuclear projects have to fulfill in order to be compliant with the EU taxonomy. The EC noted that, the criteria for both the gas and nuclear activities will be updated regularly as technology evolves.

The Platform on Sustainable Finance and the Member States Expert Group on Sustainable Finance, which must be consulted on all Delegated Acts under the Taxonomy Regulation, will have until 12 January to provide their contributions. The Commission said it will analyze these contributions and formally adopt the Complementary Delegated Act in January 2022. It will then be sent to the co-legislators for their consideration. The European Parliament and the Council will have four months to examine the document. In line with the Taxonomy Regulation, both institutions may request an additional two months of scrutiny time. Once the scrutiny period is over and assuming neither of the co-legislators object, the complementary Delegated Act will enter into force and apply. (Joint Research Centre of the European Commission, 2021)

It is also important to note that this “nuclear” renaissance will not be possible without a sound and collaborative decommissioning industry, particularly considering that 52 nuclear power plants are expected to be shut down on the same continent by 2030 (Arthur D. Little, 2021)

1.2 Objective of the Thesis

After the observation of the above mentioned trends, I would like to investigate to which extent the concept of circular economy can be applied in the nuclear sector, based on two examples, the uranium resource extraction side, since mining processes are quite energy consuming and have several long lasting impacts on the environment , as well as from the end of life site of the nuclear power fleet itself, due to the fact that in Europe alone it is planned to decommission a significant number of nuclear power plants , keeping in mind that most of the current nuclear power plants that will have to be decommissioned soon were built where almost no consideration was given to sustainable or circular decommissioning . I will also take a closer look on how the nuclear decommissioning process is handled from a legal perspective, the specific regulations that are in place, especially on a European level. At the end of my research I will point out the difficulties that are encountered when applying the circular economy concept in those two areas of the nuclear sector and also suggest possible solutions and provide suggestions to overcome these difficulties.

1.3 Research Questions

Therefore, I would like to answer the following research questions:

- In which areas of Uranium mining can circular economy be applied and to which extent?
- To which extent can circular economy be applied to the decommissioning process of nuclear power plants?
- How is the process of nuclear decommissioning handled from a legal perspective and what are the specific legal regulations in place?

1.4 General overview of Methodology

For my research I collected qualitative, descriptive data. As such a methodology is less controlled and more interpretive, my research findings, meaning the extent to which a circular economy approach can be applied to the nuclear industry will also be influenced by my personal perception.

To collect my data, I mostly used scientific articles through online libraries, relevant technical publications from the IAEA, articles from science direct, google scholar; as well as the official website of the European Commission where an update of the circular economy action plan was published (11 March 2020) and the report recently Published by the JRC on "Technical Assessment of Nuclear Energy with respect to the "do no significant harm" criteria of Regulation (EU) 2020/852 "Taxonomy Regulation". (Joint Research Centre of the European Commission, 2021)

The thematic analysis and content analysis have been performed to a smaller extent.

Given the fact that different sources are offering slight deviations when it comes to the description of the term circular economy, I decided that a thematic, qualitative analysis will be the best research approach.

2 The current status of the nuclear Industry and the definition of circular economy and the European Waste Hierarchy

2.1 Status of the nuclear industry and its decommissioning activities, with an emphasis on the European Union

According to data from 2020, currently 440 reactors are under operation worldwide, spread over 30 countries. The USA have the biggest fleet of nuclear power plants with 95 operating units, followed by France with 57 units and China with 47 reactors. Worldwide more than 190 power reactors in 27 countries are currently in the process of being shut down. 17 nuclear power reactors have already been fully decommissioned, while more and more are coming closer to the final stage of the decommissioning process. According to the IAEA it is estimated that more than 100 NPPs will be shut down by the end of the coming decade. (Marino G. , 2021) As for the European Union, nuclear power accounts for approximately 25% of the total electricity production. At the moment, 103 nuclear power reactors are operation in 13 out of the 27 EU Member states, with France being the biggest nuclear energy provider followed by Germany, Spain and Sweden. (World Nuclear Association, 2022 a), (European Commission, 2022 c). There was no information found on the number of reactors that are about to be decommissioned in the European Union.

It is important to note, that the energy policies of the different EU Member States vary, especially when it comes to the management of Nuclear Power. As it will be described later in more detail in chapter 3, only 5% of the overall material decommissioned from a nuclear power plant is highly radioactive. Around 90% can be recycled or recovered, while the remaining 5 % can be disposed of as conventional waste. Most of the material being decommissioned are concrete and metal.

Handling of the waste emerging from the dismantling of a nuclear facility, is subject to the respective standards and legislature of the concerned country and even though there are international and European standards in place, that describe how to manage these materials, the national law of the respective country overrules them, leading to significant differences on the management of the respective materials, even in neighboring countries. In France, for example, the release of material from the decommissioning process of nuclear power plants is not allowed, however in Germany the standards for recycling of materials from Nuclear Power plants are more relaxed. The unconditional release of non-radioactive clean material is allowed, "*meanwhile a conditional release with various levels, and in specific industrial areas for those slightly contaminated (which would not be released in Italy, for example) is in place*." (Marino G. , 2021)

While old nuclear power plants were designed and operated with sustainability issues not really being in place, new facilities are now being designed with decommissioning and waste management plans and consideration included from the beginning onwards, creating opportunity for circular economy and innovative designs. Reactors, for example, can be designed with in a more modular way, leading to an easier dismantling process, or construction material could be used, which allows for an easier decontamination process.
(Marino G. , 2021)

2.2 Legal framework of the European Union on the management of waste - EU Waste Framework directive

The Waste Policy provides a framework to improve waste management, stimulate innovation in separate waste collection and recycling, minimize the amount of waste being landfilled and also creating incentives to change consumer behavior. The goal is the reduction of the actual quantity of waste which is being generated and the reduction of the amount of harmful substances that it contains. (European Commission, 2022 d)

It is legally supported by the waste framework directive of the European Union, which serves as the legal framework for the treatment and management of waste in the EU. (European Commission, 2022 e) The waste framework directive defines the basic concepts related to the management of waste such as "waste", "recycling" and "recovery". Additionally, it describes the basic principles for waste management. It requires that waste should be managed:

- *"without endangering human health and harming the environment*
- *without risk to water, air, soil, plants or animals*
- *without causing a nuisance through noise or odours*
- *and without adversely affecting the countryside or places of special interest"*

(European Commission, 2022 f)
It also provides an explanation for when waste stops being waste and is considered as a secondary raw material and also defines on how to distinguish between waste and by-products.

It also introduces the "Polluter pays principle" and the "extended producer responsibility". (European Commission, 2022 f). However, the foundation for waste management in the European Union is the "Waste Hierarchy", which is set under the waste Framework Directive. It describes an order of preference for the management and disposal of waste.

2.2.1 Waste hierarchy

"Prevention and re-use of waste are the most preferred options, which are then followed by recycling (including composting), then energy recovery, while waste disposal through landfills should be the very last resort. The EU waste legislation also sets specific targets to increase the recycling of specific waste streams, such as electronic equipment, cars, batteries, construction, demolition, municipal and packaging waste, as well as to reduce the landfilling of bio-degradable waste." (European Commission, 2022 f) A graph of the waste hierarchy is depicted below.

Figure 2: Waste Hierarchy (European Commission, 2022 f)

2.2.2 The European Waste Framework directive and treatment of hazardous waste

Since hazardous waste poses a greater risk to human health and the environment than normal (non-hazardous waste), a stricter control regime has to be in place for the handling of hazardous waste. Additional obligations for the monitoring, labelling, record keeping and control for hazardous waste are provided in the waste framework directive, from waste production to its final disposal or recovery, also known as "cradle to grave". The mixing of hazardous waste with other categories of hazardous waste and non-hazardous waste, is also prohibited in the waste framework directive. There is a separate directive for the management of Radioactive waste and spent fuel. More details are indicated on in chapter 3.5.10 on the application of circular economy in the decommissioning sector. (European Commission, 2022 f)

2.3 The concept of Circular Economy

According to the European Commission, transitioning towards a circular economy is "the opportunity to transform our economy and to generate new and sustainable competitor advantages for Europe." (European Commission, 2015)

Circular economy is defined as an "economic system of closed loops in which raw materials, components and products lose their value as little as possible, renewable energy sources are used and thinking over new systems' design or systems' redesign/re-definition is at the core the core" (Zeffiros, 2019) ,as illustrated in figure 3 below.

Figure 3: The circular economy model (SRIP Circular Economy, 2022)

Going circular often means shifting away from the linear economic model. A linear business model would take a resource and turn it into waste, due to the way of how a product has been designed and manufactured. However, in a circular economy you would aim at reusing, sharing, repairing, remanufacturing, refurbishing and recycling the product in order to create a system of closed loops, aiming to minimize the use of inputs, as well as making sure that there is as little waste, and pollution as possible created. Figure 4 below depicts the difference between a linear and a circular economic model. In a circular economy, waste materials should become input of new processes through the valorization of waste. They can be recovered as either a new economic component or a recovered resource used for another industrial process or as a regenerative resource used in nature such as compost, for example. A regenerative approach, standing in contrast to the linear economy which follows a take, make, dispose scheme.

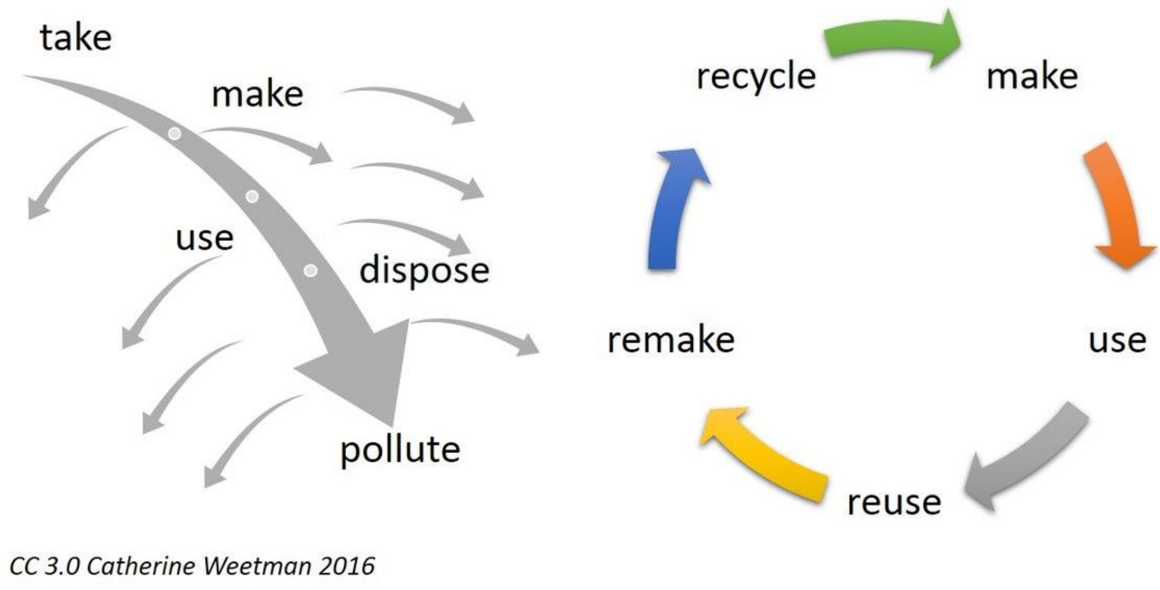

Figure 4 : Comparison between a linear and a circular economic model (Weetman, 2016)

The term circular economy is also often linked to the Sustainable Development Goals of the United Nations. It is aiming to make our economy as circular as possible by providing new solutions on how to optimize our resources and become less dependent on resources that are finite.

In a circular economy material cycles are seen as closed cycles. Therefore, waste should be reduced to the minimum amount possible and residual streams shall be used to produce new products. Toxic substances shall be tried to eliminated and residual flows are separated into a biological and a technical cycle. Producers shall take back their products after use and repair them for a new useful life (Ellen McArthur Foundation, 2022). Therefore, in this system it is important to not only recycle the materials properly, but also focus on the fact that products, components and raw materials shall remain of high quality while in this cycle.

Systematic thinking is also of high importance. Every actor involved in the economy (be it a company, person or organism) is connected to other actors, thus forming a network in which actions of one player are influencing the actions of another. Therefore, short- and long-term consequences shall be considered, not only when it comes to making decisions but also the impact of this decision will have on the entire value chain.

2.4 Commonalities and differences between the concepts of Waste Hierarchy and Circular economy

The similarity that circular economy and the waste hierarchy both share, is that the goal of both concepts is to improve the effectiveness of waste management and treatment through the reduction of environmental impacts, mitigation of resource depletion and the avoidance of waste yields, which can be summarized by the two major goals of waste management: the protection of humans and environment and the conservation of resources. "From the perspective of the lifecycle, both concepts of circular economy and waste hierarchy are considering the whole life cycle as a product, including the pre-use, use, and post use phase of the life cycle. However, circular economy puts a very strong emphasis on the design of the product, aiming at producing products in a way that they generates as little waste as possible, or in the ideal case no waste at all and that the products are designed in way that the last long and can be completely recycled at the end of their life time.

The main difference between those two concepts is that in "the concept of waste hierarchy disposal is being mentioned, while circular economy is operating in closed loop cycle." (Zhang, et al., 2022)

3 Results

3.1 Brief overview of the material consumption in the nuclear industry

Energy related material consumption

Energy related material consumption is primarily uranium ore, which is then further reprocessed through highly sophisticated chemical and physical processes and additionally added chemicals into fuel pellets, which are then inserted into the fuel rods of the reactor to start the fission process and create energy. During the mining for uranium ore, waste rock and soil is generated. In my research I will further address in more detail, to which extent circular economy can be applied to the mining process of Uranium ore.

Construction related material consumption

Major construction inputs, actually accountable for 95 % of the construction material inputs, are steel and concrete. The evaluation of material inputs of construction material is rather important, since it helps to conduct life cycle assessments for environmental impacts of nuclear systems and also plays an important role for the application of the circular economy concept which will also be addressed further in more detail. Figure 5 below provides an overview for the material flow of the nuclear fuel cycle.

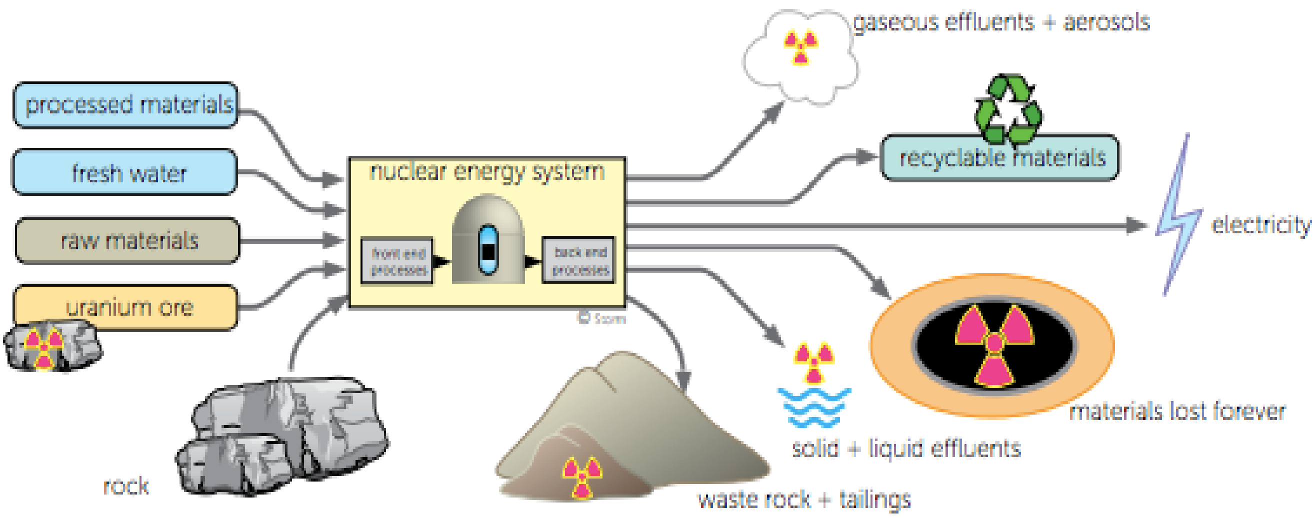

Figure 5: Material flow of the nuclear fuel cycle – materials of nuclear power, the nuclear consulting group (Leeuwen, 2019)

3.2 Understanding the nuclear fuel cycle

The Nuclear fuel cycle is defined as the set of processes and operational activities that are conducted in order to produce nuclear fuel, the radiation of the fuel, followed by storage and either reprocessing or disposal. There are two types of nuclear fuel cycles:

- Open nuclear fuel cycle: where the material is used once inside the reactor and is not reused
- Closed fuel cycle: the material is being extracted from irradiated fuel

(International Atomic Energy Agency, 2009 a)

A simplified version of the nuclear fuel cycle is depicted below in fig 6.

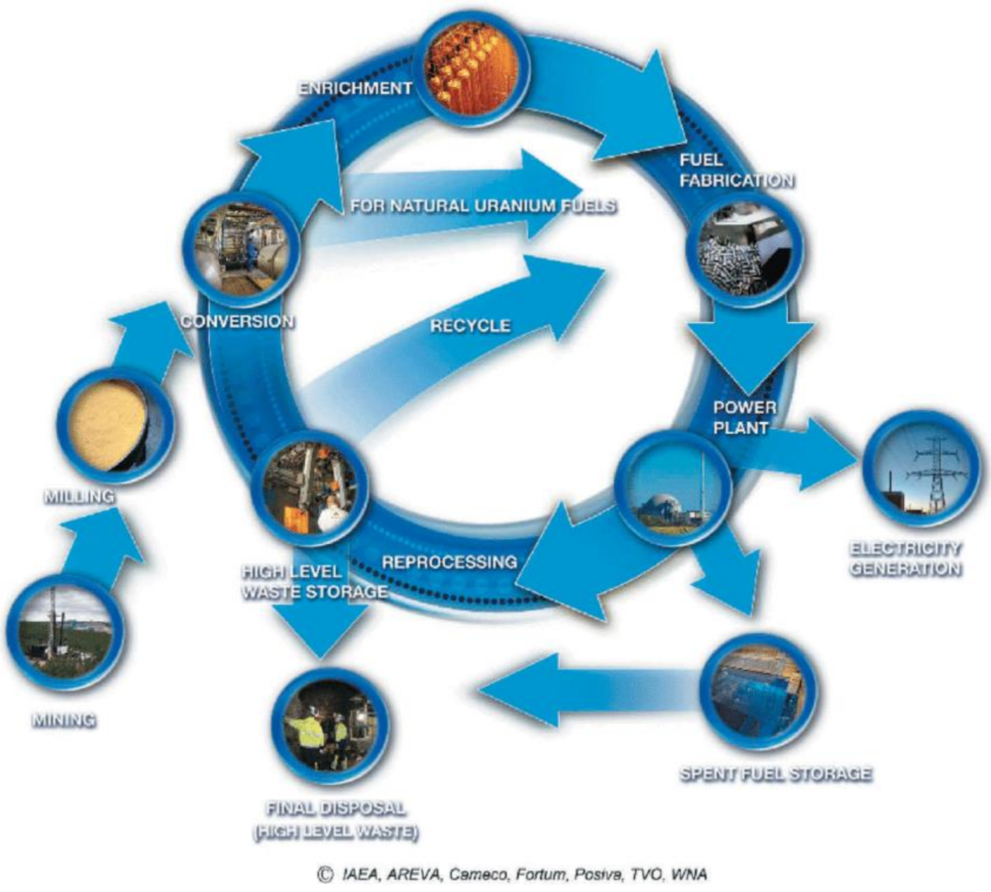

Figure 6. The nuclear fuel cycle, an overview (International Atomic Energy Agency, The nuclear fuel cycle, 2011 a)

Typically, the nuclear fuel cycle is being divided into the front end and the back end, also depicted as front end and back end processes in Figure 6. The front end entails all the activities which are relevant to the production of nuclear fuel, starting with the exploration of ore in the mines and ending with the shipping of the enriched uranium to be assembled as nuclear fuel. (Synatom, 2022)

The back end of the nuclear fuel cycle starts once the uranium is used up, after electricity production. The now used fuel is undergoes a few further steps such as temporary storage, reprocessing and then followed by recycling, before being converted into waste and then disposed. (World Nuclear Association ,2021 a)

3.3 Understanding decommissioning activities

Once the nuclear fuel cycle is complete, the decommissioning activities of the Nuclear Power plant begins. All electricity generating power plants have a certain time frame for operation, which is economically feasible. Most nuclear power plants have been designed for a lifetime of around 30 years. New generations can last from 40 to 60 years.

At the end of its lifetime, every power plant needs to be decommissioned, cleaned up and demolished, so that the used site can then be available for alternate uses and the non-radioactive material can be reused or recycled. For the case of nuclear power plants, decommissioning typically includes the cleanup of radioactive materials, as well as progressive process of plant dismantling and materials management. For the radioactive materials, additionally legal and regulatory activities are involved. (International Atomic Energy Agency, 2022)

During the phase of the final shutdown a final decommissioning plan has to be prepared which describes the decommissioning strategy in detail, inter alia stating how impacts on the environment will have to be addressed and also how materials both radioactive and non-radioactive, have to be managed. (International Atomic Energy Agency, 2022)

In order to address and research the above-mentioned issues, I will answer the following research questions: In which areas of uranium mining can circular economy be applied an to which extent? To which extent can circular economy be applied to the decommissioning process of nuclear power plants? How is the process of nuclear decommissioning handled from a legal perspective and what are the specific legal regulations in place? Those issues will be addressed in the chapters below.

3.4 Applying the circular economy concept to the front end of the nuclear fuel cycle

The front end of the nuclear fuel cycle is typically divided into four stages:

1. Mining and milling (for uranium extraction),
2. Conversion
3. Enrichment
4. Fabrication

For my research particularly the mining and milling part (uranium extraction) is of most relevance since it has the highest environmental impact. (Congressional Research Service, 2019)

Uranium Extraction

The very first step in the nuclear fuel cycle is the mining of uranium. Even though ores with high grades of Uranium do exist, the significant proportion of Uranium mining is carried out in large volumes through the extraction of low grade ore which is easily accessible. From a geographical perspective Australia, Canada, Kazakhstan, Namibia, Niger and Russia are the main producers of the World's Uranium. Over the last decade the production of Uranium has increased to almost 50 %. There are three different methods available to get Uranium out of the ore, which are:

1.Open pit

Open pit mining basically means that surficial soils and uneconomic rock is removed with the aim to get to the ore below. This type of mining is mostly chosen when the ore is close to the surface and is also creating the highest amount of waste piles. Open pit mining is generally limited to a depth of about 300m. The wastes from the open pit mining and underground mining generally consist of soil and waste rock overburden, rock excavated from underground and drill cuttings. The wastes may contain trace amounts of uranium and radioactive decay products.

2.a Underground Mining

Underground mining is chosen to get to concentrations that are located deeper down from a geological perspective, and hence open pit mining would not be feasible. The ore is first being drilled and then debris is created and transported to the surface and from there on to a mill.

2.b Milling

For both of the methods mentioned above, the concentration of uranium might be relatively low. In that case the metal has to be removed from the ore and concentrated. This is done through crushing and pulverizing the ore and adding of H2O to create a slurry.
(Ulmer-Scholler, 2022)
During this process mine tailings emerge, which contain a significant amount of radioactive waste.

3.In-situ leach (ISL)

During the process of in situ leaching the ore is not touched. Instead liquids are being used that are being pumped through the ground for the recovery of the uranium out of it. As a result, the surface mostly stays intact, and little waste rock is being generated. In situ leach may not have any surface manifestation but may lead to groundwater contamination. (Hore Lacy, 2012). After uranium is extracted from the ore, the mill tailings are likely to contain virtually all the nuclides in the uranium decay series, particularly those of U 238. It is necessary to understand the mineralogy and geochemistry of the tailings as they have a bearing on the environmental consequences of milling wastes. (World Nuclear Association, 2021 b)

The decision on which of these three methods to use depends on the consistency of the ore body, as well as economical and safety considerations. (World Nuclear Associaiton, 2021 b)

3.4.1 Waste produced during uranium mines and mills

The majority of waste that is produced during the mining and milling of uranium are waste rock and tailings. Tailings are referred to as the waste which results from the ore which is being grinded and the chemical concentration of uranium. Once dry, they have a similar consistency of fine sand. Waste rock is considered rock material which is being removed, so that access to the actual ore is enabled. Depending on its content waste rock is separated into mineralized or clean rock, depending on their mineral content. Both have to be properly managed due to the radioactivity content thereof. The radioactive elements contained therein are primarily radium 226, as well as thorium 230 and decay products associated with them. The above-mentioned waste is usually stored in specially engineered facilities for waste management, which are located close to the mills and mines.(Canadain Nuclear Safety Commission, 2021)

- **Wastes from mining and milling**

In many ways the environmental aspects of a uranium mine are the same as those of other metalliferous mines. Uranium minerals contain more radioactive elements in their ore such as radon, which develop due to the radioactive decay of Uranium (hundreds millions of years). Even though the element of Uranium as such is not very radioactive, due to the radioactivity of the ore special percussions have to be made, on top of the general environmental controls that are needed for the control of a mine of any type.

When talking about open pit mining there are big quantities of waste rock and overburden waste remaining after the operations. Normally those are being located close to the mine pit and then either used during the rehabilitation process or being revegetated and shaped at their location.

The methods chosen for mining, the management of tailings, as well as the process of land rehabilitation are subject to governmental regulations and inspections.

- **Tailings and radon**

Tailings are solid waste products that emerge from the milling operation. The contain most of the original ore and most of the radioactivity is contained therein, in particular the radium from the original ore. Sine the tailings are now located on the surface, measures have to be implemented to ensure the minimization of radon gas emission. As long as the mine is operational, the material in the tailings dam is being covered by water, so that radon emission and surface radioactivity are being reduced.

Once the mining operation is complete, typically the tailings dam is being covered with clay, so that the radiation levels are being reduced to those that are normally experienced in the orebody region, allowing for the establishment of a vegetation cover.

- **Waste water**

Run-off water which came from the mine stockpiles, as well as waste water from milling operations is being collected in "specifically designated " ponds, where heavy metals and other contaminants are being recovered under isolation. The liquid remainder is then either being taken care of through natural evaporation or through recirculation into the milling operation.

The processed water which is being discharged from the mill still contains traces of radium, as well as other metals. This waste water is being taken care of through evaporation. The therein contained metals are then being retained in secure storage.

For the process of in-situ leaching, as mentioned above, the orebody is not being dislocated. The uranium is being recovered through the circulation of acidified and oxygenated groundwater though it, through the use of recovery and injection wells. "The saline quality of this groundwater in Australian ISL mines makes it far from potable in the first place, and after the uranium is recovered, oxygen input and circulation are discontinued, leaving the groundwater much as it was." (World Nuclear Association, Environmental Aspects of Uranium Mining, 2022)

However, the main environmental concerns come into place when it comes to the pollution of groundwater outside of the orebody, with the main goal to leave the immediate groundwater as close as possible to its previous state.

- **Rehabilitation**

Apart from the tailings wastes, equipment which is not being able to be reused at the end of the mine operation, is in most cases is being buried together with the tailings.

At the end of the mining operations, the tailings are being filled up with soil and clay with the main aim to reduce radon emission rates as well as gamma radiation level to those who are occurring naturally in the region. The tailings are also being covered with rock to resists erosion. Once those processes are complete, a vegetation cover is being established.

"At the conclusion of mining, tailings are covered permanently with enough clay and soil to reduce both gamma radiation levels and radon emanation rates to levels near those naturally occurring in the region, and enough rock to resist erosion. A vegetation cover is then established". (World Nuclear Association, 2022 b)

3.4.2 Applying the Circular Economy principle to Uranium Mining

From the perspective of circular economy, the technology which is needed for sustainable mining should be an environmentally sound technology, meaning that there are less emissions and also a higher resource efficiency. Additionally, the products and waste should be recycled at a higher rate.

Circular economy applied to the mining industry would mean that the economic system should follow the characteristics and natural ecological rules of mineral resources and mineral products and also take highly efficient and comprehensive utilization of mineral resources at its core.

The principle of circular economy is mostly referred to as reduce, reuse, recycle. Reduction is referring to the method of input, which should aim at the reduction of the flow of materials and energy into the process of production and consumption. Reusing is aiming at extending the life time of the product or at least the materials contained therein for a s along as possible. Recycling refers to the method of output with the aim of materials returning to renewable resources after being used. In the mining industry applying the reduce, reuse, recycle principle could mean the following:

- Reduce

"*During the process of exploitation, processing and utilization of the mineral resources, reduction can be implemented through:*

- *Reducing the efficient exploitation of resources by mechanization, automatization and exploitation optimization*
- *Reducing mining dilution ratio and ore loss ratio and enhancing the recovery rate of mineral-processing and smelting to improve the total recovery of resources by studying mining processing technology of complex difficult mining and refractory ore*
- *Raising the comprehensive benefit of resource development by reducing emission of various pollutants such as tailings, gangue and mine waste water."* (Zhao, Zhang, Zhongxue, & Qin, 2011)

- “Reuse” and higher recovery efficiency

On the one hand, this can be displayed in the re-utilization of mine waste water. The main sources of mine wastewater are discharged ore pit water and waste water, which is discharged from the concentration. There are different chemical, biological and physical methods available for wastewater treatment. The goal of all those principles is to separate the harmful substances from the non-harmful ones. Many plants today operate on a closed cycle technology, which means that the water is not being discharged. Instead it is being reused inside the system.

On the other hand, attention also needs to be paid to the development of tailings and the minerals that are associated with them. Here waste can be transformed into valuables and or reduced. With state-of-the-art mineral processing technology, components that were difficult to recover can be recovered now. This means that the ore and tailings that previously were treated as waste rock can be re-utilized and therefore additional minerals can be extracted, leading to increased resource extraction and less waste. In the case of uranium tailings and waste rock those could be base metals such as (Ni, Cu, Co, Mo and Li) as well as rare earth elements that can be recovered. Of course, there majority of the waste is also waste rock and waste tail, unfortunately due to the radioactive properties this material cannot be re-utilized, whereas in the case of other mining industries it could be re-utilized as building material.

- Recycling

Recycling means reducing the creation of waste to the highest extend possible, though the processing of mineral resources that have completed their functions, making them available resources again so that they can re-enter the market.

As previously described in the chapter on the nuclear fuel cycle, the fabrication of fuel is a rather complicated process consisting out of 4 steps, namely mining and milling, conversion, enrichment and fabrication. In a closed nuclear fuel cycle the material is being extracted from irradiated fuel. “*The spent fuel contains uranium (96%), plutonium (1%) and high-level waste products (3%). The uranium, with less than 1% fissile U-235 and the plutonium can be reused. Some countries chemically reprocess usable uranium and plutonium to separate them from unusable waste. Recovered uranium from reprocessing can be returned to the conversion plant, converted to UF6 and subsequently re-enriched. Recovered plutonium, mixed with uranium, can be used to fabricate mixed oxide fuel (MOX).*” (International Atomic Energy Agency, 2011 b), (World Nuclear Associaiton, 2022 c)

3.5 Circular economy in the nuclear decommissioning sector

3.5.1 Understanding the process of nuclear decommissioning

Decommissioning refers to the technical and administrative actions that have to be taken to remove all or some of the regulatory controls from an authorized facility, so the facility and its site can be recycled and reused. It includes activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.

"It is a normal part of a nuclear facility's lifetime and has to be considered at the earliest stages of its development. As part of a facility's initial authorization, a decommissioning plan is developed that demonstrates the feasibility of decommissioning and provides assurance that provisions are in place to cover the associated costs. At the final shutdown, a final decommissioning plan is prepared that describes in detail the decommissioning strategy, how the facility will be safely dismantled, how radiation protection of workers and the public is ensured, how environmental impacts are addressed, how materials – radioactive and non-radioactive – are to be managed, and how the regulatory authorization for the facility and site are to be terminated."

(International Atomic Energy Agency, 2022)

3.5.2 Application of Circular Economy in the nuclear Decommissioning sector

Addressing sustainability considerations and moving towards implementing circular economy principles in nuclear decommissioning gives the opportunity to transform the engagement on decommissioning with a range of stakeholders, including decision-makers and the general public. Doing so effectively, could build a dialogue centered on the development of progressive and sustainable solutions and at the same time create a value to society.

While, the concept of sustainable development (or sustainability) has existed for more than 30 years, its use in the context of the nuclear decommissioning industry is relatively recent. The reason for that being that most of the current reactors that are still under operation, were built before the concept of sustainability came into existence. Currently, more than 190 Nuclear Power Reactors in 20 countries across the globe are currently in the state of shut down. Out of these, 17 have already been fully decommissioned, while others are about to approach the final stages of the decommissioning process. In the next decade, it is foreseen that up to an additional 100 power reactors are about to be shut down. (Marino G. , 2021)

As a result, the topic of sustainable decommissioning is coming to the fore and the questions of the application of circular economy, as well as the waste management hierarchy are gaining momentum. However, given the above-mentioned circumstances the concept of circular economy can only be applied after the reactor design phase, since sustainability and circularity was not prioritized while those reactors were build. However, significant lessons can be learned for the design of new reactors, allowing for them to be built in a more sustainable and circular manner.

Also, given the fact that the integration of sustainability principles in nuclear decommissioning is a new field, there is no common guidance on its application in practice for now. Therefore, for my research I will pay particular focus to the 3R - reduce, reuse, recycle as mentioned previously and examine to which extent the concepts of recycling be applied to the nuclear decommissioning sector which would mostly entail maximizing the amount of clearable material to be released from regulatory control, to be reused in the nuclear other sectors such as the construction industry and maximizing on-site recycling. (International Atomic Energy Agency, 2019)

3.5.3 Management of Nuclear Waste on an European level – Legal background

In the European Union the regulation of nuclear facilities dates back to the start of the European Community. Together with the Treaty for the European Coal and Steel Community, also known as ECSC, the treaty for the European Atomic Energy Community (EURATOM), was one of the first treaties of the European Communities, which entered into force on the 1st of January 1958. Further in July 2011 the "Radioactive Waste and Spent Fuel Management Directive" was established under the EURATOM treaty. The Directive 2011/70/Euratom requires that:

"

- *EU countries have a national policy for spent fuel and radioactive waste management*
- *EU countries draw up and implement national programmes for the management of these materials, including the disposal, of all spent nuclear fuel and radioactive waste generated on their territory*
- *EU countries should have in place a comprehensive and robust framework and competent and independent regulatory body, as well as financing mechanisms to ensure that adequate funds are available*

- *Public information on radioactive waste and spent fuel and opportunities for public participation are available*
- *EU countries submit to the Commission every three years (starting August 2015) national reports on the implementation of the directive, on the basis of which the Commission will draft a report on the overall implementation of the directive and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects*
- *EU countries carry out self-assessments and invite international peer reviews of their national framework, competent authorities and/or national programme at least every ten years (by August 2023)*
- *The export of radioactive waste for disposal in countries outside the EU is allowed only under strict conditions "*

(European Commission, 2022 g)

It is important to add that due to the radiological characteristics, the treaty has limitations in its scope, given the limits on what can be regulated und controlled under the treaty and what still remains under the auspices of the respective Member States. "The EU has no competences in regulatory fields such as operational safety of nuclear power plants, management and safe disposal of radioactive waste, storage or disposal facilities and decommissioning of `installations." (Fouquet D., 2019)

Those important aspects of the nuclear industry are under the responsibility of the respective authorities, which in most cases mean the regulator. The International Atomic Energy Agency also plays a crucial role here, when it comes to providing guidance and best practice examples.

3.5.4 Understanding the Material Flow of a Nuclear Power Plant

Figure 7: Material flow in nuclear facilities, (SOGIN, 2019)
SOGIN to the International Atomic Energy Agency, presented by Paola Maoddi, February 16, 2021

The figure above depicts the material flow of a nuclear power plant and thereto related facilities. It shows that the vast bulk of material (metals and concrete around 89%) is “clean” and can be released from radiological protection control after cleaning and sorting for recycling purposes.

Considering that the total material input for a NPP and related facilities would be around 1.277.000,00t, out of these 1.217.000,000 t would be conventional material of which 72.000,000t would be conventional waste and 16.100 t would be conventional waste from possible milling operations. 1.142.000,00 t are metals and concrete of which 12.372,000 t are radioactive material which can be released after decontamination, accounting for 89% of the overall waste from a nuclear power facility, which can be recycled. 47.400, 000 t are radioactive material, consisting of 46.500,000 t of radioactive waste and 911,000 t of spent nuclear fuel.

3.5.5 Overview of Recent Practices in Radioactive Waste Management as Part of Decommissioning

The management of radioactive and non-radioactive waste is an important step in the overall decommissioning process. Its aim is to reduce the volume of the waste to be conditioned for interim / final disposal and recycling to the highest extent possible according to clearance legislations and regulations of the respective country. The volume of the waste is normally reduced by decontamination and specific treatment processes.

Generally speaking, depending on the waste type, the following methods described below are used for the management of waste.

- **Characterization, Sorting and Segregation**

Waste needs to have a deep characterization and to be segregated onsite, mostly according to its homogenous group and physical and chemical properties of the material.

In order to achieve a well working, optimized, safe, and cost-efficient treatment and clearance process for the materials and components of larger size arising from decommissioning projects, a proper knowledge of the radiological properties for the material to be treated and cleared is necessary.

- **Decontamination**

Structures and systems form the majority of the waste arising from decommissioning. Generally, surfaces are contaminated and seldom activated. Surface decontamination, by dry processes (e.g. blasting) or wet processes (e.g. chemical or electrochemical), supports reducing the radioactive waste volume as it provides conditions for reclassification of the waste

- **Volume reduction**

Depending on the waste type, thermal treatment is used to reduce the volume, (incineration, pyrolysis) are used for organic material and plasma heating for waste mixtures.

Melting of metals is used to homogenize the radioactivity and by then allow high precision analysis of the radioactivity content (i.e. generate good conditions for clearance). The melting process will also transfer several nuclides from the metal to the slag and the off-gas system.

Overview of the Process

Figure 8. provides an overview of the steps mentioned before, up to and including decisions on release of the material from regulatory control by clearance (see following sections) or sentencing the material as radioactive waste.

First the waste is being initially characterized due to its history and through visual examination, for example and after that it is being categorized according to the risk that is posed by its contamination. It is being differentiated on whether there is an extremely small risk of contamination, a small risk of contamination, check if the material is being contaminated above clearance levels.

If the risk of contamination is extremely small, then no further actions are needed.

If the risk of contamination is small, then the activity of the material has to be measured and it has to be controlled, whether the material is complaint with the regulations in place.

If there is a risk of contamination or the material is contaminated above the clearance level, then a judgement procedure has to take place, before the material will proceed to the decontamination procedure. After that the activity of the material is being measured and a control with compliance is being undertaken. If, after the activity measures the control with compliance is not passed, the material has to undergo the judgement procedure again.

If the control with compliance is passed, the material is being reviewed and approved, with the final stage being its release into the conventional waste cycle.

If on the other hand during the judgement procedure the material is being classified as radioactive waste, then it has the undergo the necessary procedures foreseen for the management of radioactive waste. (International Atomic Energy Agency, 2019)

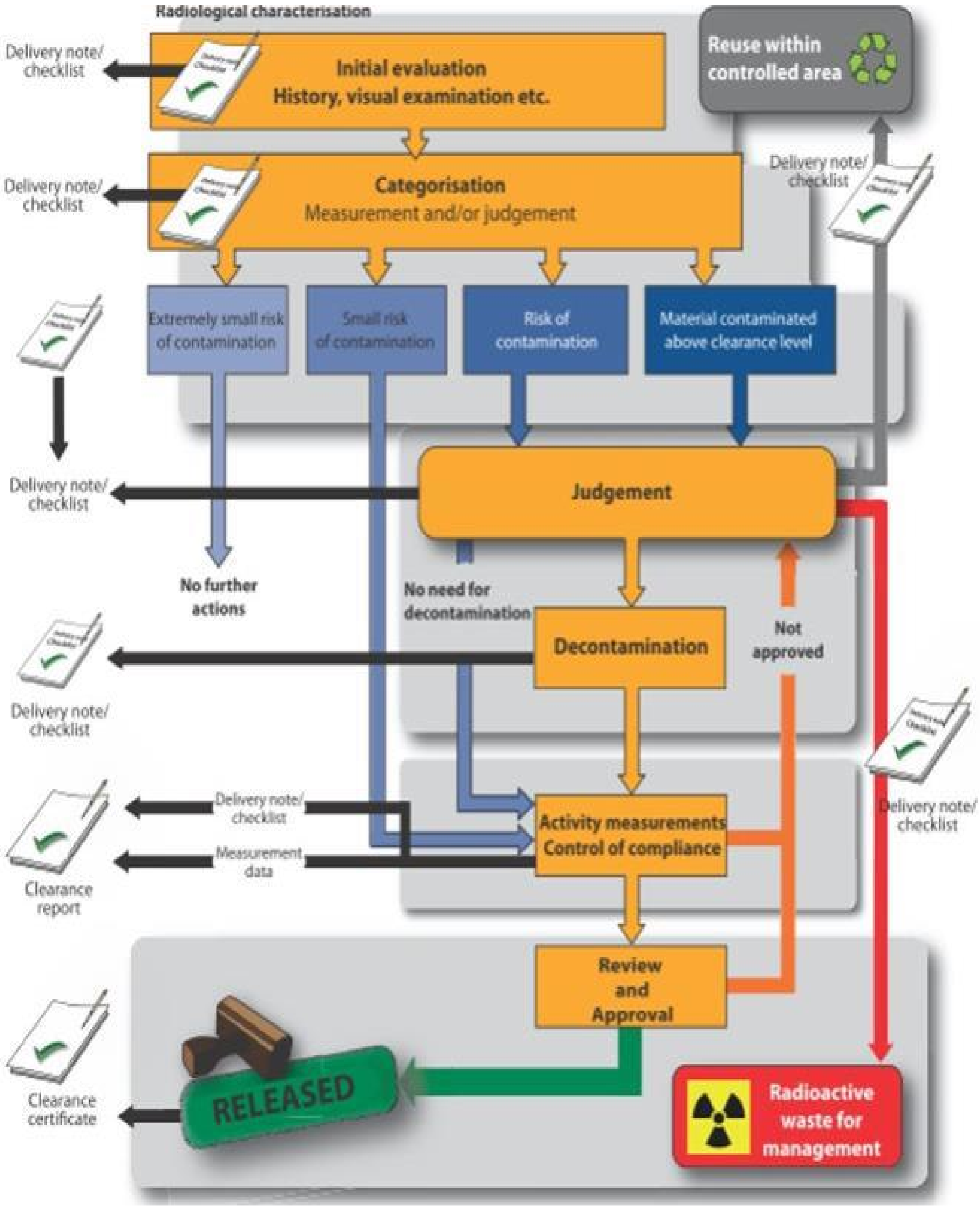

Figure 8, An overview of the radiological characterization process, International Atomic Energy Agency, 2019

(International Atomic Energy Agency, 2019)

3.5.6 The way from an NPP into the regular waste cycle

Material that is related to Nuclear Power facilities underlies strict legal criteria and is subject to regulatory control, which depend on the respective state and its regulator, as previously mentioned in this chapter.

The International Atomic Energy agency provides guidelines and best practice examples on the management of radioactive waste. However, as mentioned previously, it us up to the respective government to decide on their particular guidelines and mechanisms in place.

To establish under which category which type of waste is falling, it has to be characterized. Waste characterization is the determination of the radiological, chemical and physical properties of waste and lays the foundation for determining on how to treat, handle, process store or dispose of radioactive waste. Physical waste characterization involves inspection which helps to determine the physical from of the waste (solid, liquid or gaseous) and other physical properties such as dispersibility and comprehensive strength that might be needed in order to meet the requirements for disposal. Chemical properties refer to the determination of chemical components and properties. They are calculated through an analysis of the waste samples as well as basis knowledge of the process that generated the waste. Radiological properties are the inventory of radionuclides (activity concentration, decay products and half-lives), dose-rate, heat generation, radioactive gas. (Noynaert, 2013)

According to the International Atomic Energy "The Radioactive waste shall be characterized and classified in accordance with requirements that are established or approved by the regulatory body, at various steps in the predisposal management of radioactive waste ". (International Atomic Energy Agency, 2007). The IAEA indicates six classed of waste that are used for the basis of the classification scheme:

1. Exempt waste:

Is material to be released from regulatory control. It has to be either cleared, exempted or excluded from regulatory control for radiation protection purposes. Exempt waste is the most relevant type of waste for my research, in view of Circular Economy considerations and will be examined in more detail in the next chapter.

2.Very short lived waste (VSLW):

This is waste that can be stored for decay over a limited period of time (up to a few years) and is subsequently cleared from regulatory control based on the arrangements that are approved by the regulatory body, for uncontrolled disposal, use or discharge. This waste class mostly includes primary radionuclides that have a very short half-life. They are often used in research and for medical purposes.

3.Very low-level waste (VLLW):

This type of waste does not necessary meet the criteria for exempt waste, however it also does not need a high level of containment and isolation. Therefore, it can be disposed of in near surface landfill type facilities that have limited regulatory control. These landfill type facilities can also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in VLLW are generally very limited.

4. Low level waste (LLW):

This type of waste is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation, as well as containment for periods ranging up to a few hundred years. It is suitable for disposal in specifically engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration and also long-lived radionuclides, however only at relatively low levels of activity concentration.

5. Intermediate level waste (ILW):

Due to its content, particularly of long-lived radionuclides, this type of waste requires a higher degree of containment and isolation then the one which is provided for near surface disposal. ILW can contain long lived radionuclides, mostly alpha emitting radionuclides that will not decay to a level of activity concentration which is acceptable for near surface disposal. Therefore, waste in this category requires disposal at greater depths (ranging from tens of meters to a few hundred meters).

6. High level waste (HLW):

This type of waste has such high levels of activity concentration, which enables it to generate significant quantities of heat through the radioactive decay process or contains high amounts of long-lived radionuclides that need to be considered during the design of a disposal facility. It is being disposed of in deep, stable geological formations, whose depth is several hundred meters or even more below the surface

The graph depicted below helps to get a better understanding of the waste classification scheme. The vertical axis shows the activity content and the horizontal axis represents the half-lives of the radionuclides that are contained in the waste.

In some cases, also the amount of activity and not the concentration is used to determine the specific class of the waste. The higher the level of activity, the more important it is that waste is being isolated and contained. The lower range of the vertical axis indicates activity contents below clearance levels, the waste can be managed without the consideration of its radiological properties.

Half-lives of radionuclides (horizontal line) can range from very long (over thousands of years) to very short (only few seconds). Looking at safety standards for radioactive waste, a radionuclide who's half live is below 30 years is considered to be a short-lived radionuclide.

"The limitations that are placed on the activity (total activity, specific activity or activity concentration) of waste, that can be disposed of in a given disposal facility, depends on the physical, radiological, chemical and biological properties of the waste as well as on the particular radionuclides that it contains."

(International Atomic Energy Agency, 2004)

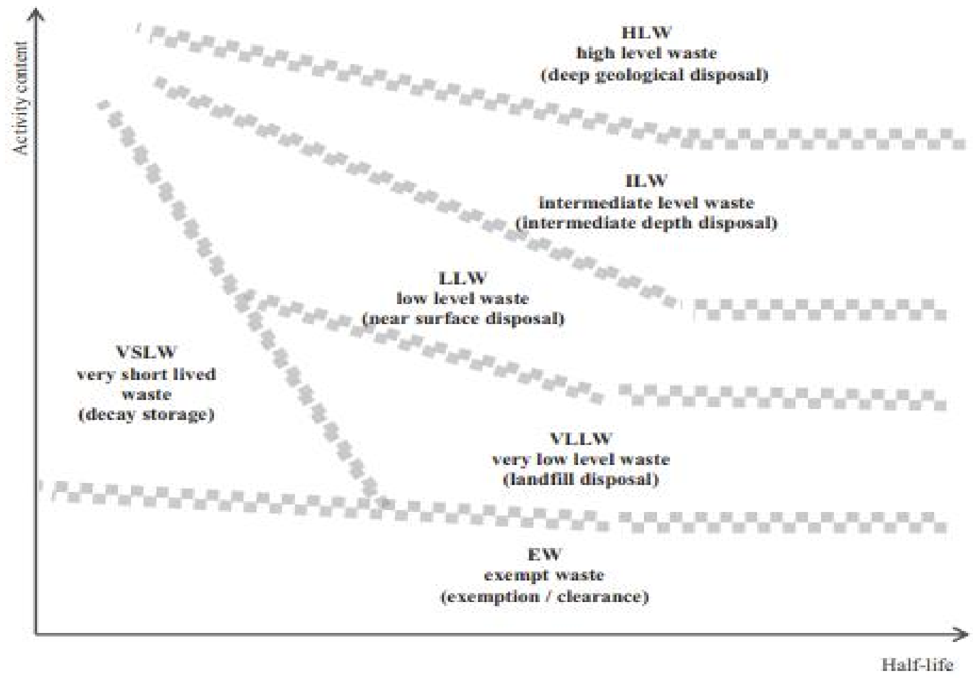

Figure 9, Conceptual illustration of the waste classification scheme, International Atomic Energy Agency 2009,
(International Atomic Energy Agency, 2009 b)

3.5.7.1. Difference between the concepts of exclusion, exemption and clearance

The safety guide of the International Atomic Energy Agency on the application of the concepts of exclusion, exemption and clearance provides and assists member states with practical guidance. However, the implementation depends on the retrospective government. A quantitative description is provided from the side of the IAEA and the national regulator has then to establish the decision on the proper application of the respective criteria.
The concepts of exclusion, exemption and clearance establish the scope of regulatory control and are an intrinsic part of the graded approach to regulation. The definition of the three concepts is described below.
(International Atomic Energy Agency, 2009 b)

Exclusion:

For some types of radiation exposures there are no realistic steps that can be implemented to control the source or the magnitude of exposure. Therefore, these sources and exposures are generally to be excluded from regulatory control.

IAEA definition:
"The deliberate excluding of a particular type of exposure from the scope of an instrument of regulatory control on the grounds that it is not considered amenable to control through the regulatory instrument in question." Examples include potassium-40 in the body and cosmic radiation at the earth's surface."
(International Atomic Energy Agency, n.d)

Exemption

Some sources of radiation contain such a low level of risk that they can be exempted from regulatory control.
IAEA definition:

> *"The determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure and the potential exposure due to the source or practice are too small to warrant the application of those aspects or that this is the optimum option for protection irrespective of the actual level of the doses or risks."* (International Atomic Energy Agency, n.d)

Clearance

"The concept of clearance is defined by the International Atomic Energy Agency (IAEA) as the removal of radioactive objects and materials within authorized practices from further regulatory control, which is applied for radiation protection purposes. Compared to the concept of exemption, clearance can be seen as the process of relinquishing material and substances from regulatory control, while exemption is the process of deciding that no regulatory control is necessary from the outset." (International Atomic Energy Agency, n.d)
Clearance is based on the concept of triviality of exposure, generally meaning:

"• *the radiation risks to individuals caused by the practice or source be sufficiently low as to be considered trivial;*

• *the collective radiological impact of the practice or source be sufficiently low as not to warrant regulatory control under the prevailing circumstances; and*

• *the practices and sources be inherently safe, with no appreciable likelihood of scenarios that could lead to doses above dose limit*." (International Atomic Energy Agency, n.d)

"In quantitative terms, this is generally related to the stipulation that the effective dose expected to be incurred by any member of the public, due to cleared materials, is of the order of 10 μSv or less in a year. It is implicit in the concept of clearance that materials, once cleared, are subject to no further regulatory restriction or control. Consequently, cleared waste may be treated as normal waste; and materials cleared for reuse or recycling may be sold or transferred to any other party and used for any purpose without being considered to be radioactive. "
(OECD Nuclear Energy Agency, 2008)

Conditional clearance

Waste underlying the conditional clearance criteria, might be for example concrete to be recycled for road construction or metal to be recycled for the metal industry. For this type of clearance, it is normally required that special conditions that are given in the regulations are met, or that a special permit has to be obtained from the regulator. One example for conditional clearance are metal ingots from a nuclear facility licensed for nuclear treatment. "*The ingots are conditionally cleared and melted together with other metals forming products that can be used in the public domain*." (World Nuclear Assosciation, 2019)

All of the above-mentioned processes free the material and sources from regulatory control, meaning that it is no longer subject to special waste management criteria and can therefore enter the conventional waste cycle, making it available to be considered for circular economy purposes. Generally, most of the material leaving regulatory control are subject to clearance, the process of exclusion and exemption are not as common.

3.5.8 Disposal as radioactive waste

Waste, which doesn't fall under the clearance, exemption or exclusion criteria has to be managed as radioactive waste and is subject to the respective regulator and nuclear law. As already listed above VSLW, VLLW, LLW, ILW, HLW have different characteristics and have to be managed accordingly.

The main objective of a waste repository is to isolate waste for a time frame long enough, so that its radioactivity can decay down t an acceptable level stipulated by law. For some types of wasted mentioned above, a few generations are considered enough, for others, however, an isolation for over thousand years is required. Globally, different types of repositories have been developed such as surface and near surface repositories and also deep geological repositories to manage high level waste. The design of these repositories is taking into account the properties of the waste that has to be disposed of, the geological properties of the respective site and also the respective legislation that applies to the site.

The two most common options for radioactive waste disposal are near surface disposal and deep geological disposal. Near surface disposal is taking place at ground level or below ground level in caverns. The depth here is usually around 10 m. The suitable waste types for near surface disposal are low-level waste and intermediate-level waste. Many countries such as USA, UK, Sweden, Spain, Netherlands, Japan, France, Finland and the Czech Republic. Additionally, near -surface disposal is implemented in Sweden and Finland for low-level waste and short-lived intermediate-level waste.

As for deep geological disposal the depths for mined repositories are between 250m and 1000m. For boreholes they range from 2000m to 5000. The suitable waste types for deep geological disposal are long-lived intermediate-level waste and high-level waste (including used nuclear fuel). (Word Nuclear Association, 2022 d)

3.5.9 Taking a brief look at non-nuclear industry approaches

Sustainability and circular economy principles - the perspective of the demolition and construction sector

As construction and demolition waste represents a large portion of the total waste produce in Europe (about 1/3 of the total), and it includes many different waste streams coming from

different sources and sectors, it has become an important part of the problem but also solution to achieve an efficient circular economy. The European Union is very active in promoting a change of thinking and fostering change related with circular economy. In 2020 the new Circular Economy action plan was adopted by the European Commission, which serves as one of the main building blocks of the European Green Deal, where the construction sector contributes a significant part to it. Under this umbrella, the European Union is also funding several projects and initiatives to analyse and demonstrate best practices related with circular economy and construction.
(European Commission, 2022)

In relation to decommissioning, the European demolition industry offers useful knowledge of best practices and knowledge from the non-nuclear activities, such as auditing, assessment, demolition process (project design and management, methods and means), decontamination of non-nuclear hazardous waste (such as asbestos, PCB, lead, … and other substances commonly found in convention demolition and in other industries).

Since there are diverse sources of waste in construction and demolition, the examples are usually linked to specific materials (such as concrete, glass, gypsum, …) and the best practices refer to the processes (selective demolition, collection schemes, experimental products etc.) more than specific sectors or industries, which is again useful for adoption for guidelines of nuclear decommissioning. It is also important to highlight that outside the nuclear sector, the number of hazardous substances and hazardous waste present in any demolition operation are growing significantly. This is forcing a change on the processes and methods, which not only affects the demolition industry but also any sector requiring demolition operations, where lessons can be learned.

As a result, is can be said that there is an extensive amount of knowledge and experience available in the non-nuclear sectors, both about decommissioning and circular economy. Most specially, the demolition industry has significant expertise in the processes, means and methods, which can be shared with the stakeholders involved in nuclear operations.

4 Conclusion

The goal of a circular economy is the minimization of waste, as well as the most efficient use of resources, starting with the design of the product in mind. In an ideal scenario, the product life cycle would be closed completely and there would be no generation of waste at all.
Circular economy applied to the uranium mining sector would mean that the technology which would be used for mining should be a sound one, producing less emissions and also aiming at higher resource efficiency. Additionally, the products and waste generated should be recycled at a higher rate. This is of particular importance for the mining part of the nuclear industry, since this process has the highest CO2 emissions, keeping in mind that nuclear energy generation itself is CO2 neutral. Looking at the 3R of circular economy: reduce, reuse, recycle mainly recycling can be applied in the uranium mining sector. The minerals contained in the uranium tailings can be transformed into valuables, meaning that ore which originated as waste rock can be recycled for additional minerals, which leads to increased resource extraction and less waste. In the case of uranium tailings and waste rock those could be base metals and rare earth elements that could be recovered.

Application of the circular economy concept in the nuclear decommissioning sector could lead to smaller amounts of waste to be disposed of and provide waste management solutions, that have a higher economical value. Another benefit could also be added value to society. Providing scientific and solid facts about the application of the circular economy concept in the nuclear industry would set an important signal to the general public towards the acceptance of the nuclear energy sector. Together, these factors would lead to several important benefits such as the increase in sustainability, smaller amounts of waste and last but not least decreased costs.
However, as mentioned previously, the application of the circular economy concept in the nuclear sector is not a straight forward one. Since most of the nuclear power plants that will have to be decommissioned soon, were built before the concept was in place, almost no consideration was given to sustainable and circular decommissioning. Given these circumstances, currently the concept of circularity can only be applied after the reactor design phase. Still, significant lessons can be learned from previous experience and applied to the reactors currently under construction, through designing them in a more modular way, which would allow for easier dismantling, or through the use of construction material, that would allow for an easier decontamination process. (Marino G. , 2021)

It is also important to increase the efficiency for the coordination between the management of radioactive waste and decommissioning, since the efficient management of radioactive waste also means reduction of waste volume and therefore would contribute to a circular economy. Ideally the waste should be segregated right at the source and treated accordingly. Here, the application of the waste management hierarchy also plays an important role.

The achieve the best optimal solution for the implementation of a sustainable nuclear decommissioning industry, it is important for the respective regulators to find an appropriate balance between financial, social and environmental concerns, such as the proper treatment specific waste streams and also possible radiological risks.

Efficiency in cost reduction could be achieved through a better harmonization process for the management of waste emerging from nuclear power plants across the European Union or even to begin with, between neighboring states. As already previously mentioned, only 5% from the total amount of waste from a nuclear power plant is highly radioactive. Around 90% can be recycled or recovered, while the remaining 5% can be disposed of as conventional waste. Most of the material being decommissioned are concrete and metal. (Marino G. , 2021)
The management of such waste varies greatly between EU Member states. There are international and also European guidelines existing, but they are overridden by the national law of the concerned country. In France, for example the release of material from the decommissioning process of nuclear power plants is not allowed. In Germany on the other hand, the standards for recycling of materials from Nuclear Power plants are more relaxed, meaning that the unconditional release of non-radioactive clean material is allowed. In Italy, for example, the unconditional release once the material is through the radiological control system is enforced. (Marino G. , 2021)
Here it would make sense to have stricter overarching laws on the management of radioactive waste, where a certain synergy is given between the member states concerned. Expertise could be shared, waste from several states could be managed in specially dedicated facilities, which would ideally to bigger amounts of recycled waste lead and a reduction of costs, leading to a higher application of circular economy in the nuclear sector on a European level.
Some progress has already been made in this area. Several Member states of the European Union and members to the International Atomic Energy Agency have adopted clearance criteria and clearance levels into their national legislation. Once material is labeled as cleared,

its legal status changes, meaning that it is no longer subject to regulatory control. At this point the regulation from the conventional waste sector comes into effect

Several member states of the European Union and members to the International Atomic Energy have transposed these clearance criteria and clearance levels into their national legislation and the criteria for clearance are the same in the current EURATOM Basic as well as IAEA Safety standards. The fact that there is a single set of criteria in the international regulatory framework has led to significant international harmonization, however still leaving big room for further improvement.

Furthermore, guidelines that asses the sustainability and circularity of the nuclear decommissioning sector in systematic manner, would be beneficial. At present no such guidelines are existing. Through the development of such guidelines the implementation of circular economy principles, as well as the consideration of sustainability principals would be much easier, since they would lead to a wider consistency in waste handling approaches, as well as greater progress in reporting and last but not least enable benchmarking between different programs and initiatives on a European and international level.
Here one could turn to the experience that is already available outside the nuclear sector, on both decommissioning and circular economy levels. The construction industry, being the main resource for resource consumption and waste generation in Europe, should be pointed out specifically, since there is a wide amount of expertise, as well as methods and means are available, which can be very useful for stakeholders working in the nuclear sector.

Can circular economy be applied in the nuclear sector? The answer is yes, and that some parts of the nuclear sector already are circular, as was shown in my research. However, it is important to highlight that the additional radioactive properties will always pose a challenge in the nuclear mining as well as the decommissioning sector. The most important step would be to establish particular guidelines describing and laying out the proper implementation of circular economy principles in the nuclear sector to enable benchmarking and cooperation on a European and international level.

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