



# Life cycle resource use of nuclear power generation considering total material requirement

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## ABSTRACT

The use of life cycle assessments to estimate the environmental impact of nuclear power generation has become increasingly common. Despite this, the volume of resource extraction in the lithosphere has not been sufficiently considered. In this study, the total material requirement (TMR) was used as an indicator in an analysis of the life cycle resource use of nuclear power generation, and the uncertainty associated with the grade of the uranium ore was evaluated. It was found that the resource use of the closed cycle in reprocessing spent fuel using MOX fuel is approximately 26% lower than that of the open (once-through) cycle. According to the representative data employed in this study, the TMR of nuclear power generation varied depending on mining methods, increasing in the following order: in-situ leaching, underground mining, and open-pit mining. Note that results for specific mine sites differ significantly depending on the ore grade and strip ratio. The results also show that the global warming potential (GWP) and TMR of nuclear power generation differ considerably and that greenhouse gas emissions are less affected than resource use by the mining method. Furthermore, the TMR of nuclear power generation is considerably lower than that of thermal power generation and is similar to that of renewables. It can be concluded that nuclear power generation is not only favorable from the perspective of global warming, as widely acknowledged, but also from the perspective of natural resource use in the narrative of life cycle analysis.

## 1. Introduction

A dramatic change in the energy landscape has occurred in recent decades due to the effort to address global warming. In response to a marked increase in global energy demand, the excessive use of fossil fuel has accelerated greenhouse gas (GHG) emissions. To mitigate the potential damage caused by huge amounts of GHG emissions, nuclear power is being promoted as a panacea to many of society's energy problems.

A comprehensive evaluation of the GHG emissions of nuclear power can be made using life cycle assessment (LCA) methods (Warner and Heath, 2012). Numerous studies on life cycle cumulative energy consumption and GHG emissions related to electricity generation by nuclear power plants have been published (Lenzen, 2008), and interest in the LCA of nuclear power generation has been continuously increasing (Koltun et al., 2018; Wallbridge et al., 2013; Ding et al., 2017). In a recent study, the LCA of a fourth generation (4G) nuclear power plant was carried out (Koltun et al., 2018). In another analysis of the life cycle environmental impacts, Poinssot et al. analyzed two different nuclear

fuel cycle routes: the open fuel cycle and the closed fuel cycle (Poinssot et al., 2014). Ashley et al. evaluated the life cycle GHG emissions by considering the mixed nuclear fuel cycle of uranium with thorium (Ashley et al., 2015) for an effective use of mine waste (Gosen et al., 2009). Notwithstanding the uncertainty surrounding the global uptake of nuclear energy generation, the exploration of the LCA of the generation of nuclear power is important.

The life cycle stages for nuclear power include the uranium mining stage, the uranium milling stage, the conversion to uranium hexafluoride, enrichment, fuel fabrication, reactor construction, reactor operation, decommissioning, fuel re-processing, nuclear waste storage, nuclear waste disposal, and transport (Lenzen, 2008; Fthenakis and Kim, 2007). Most of the early studies on the LCA of nuclear power cover the major stages, such as plant construction, fuel processing, facility operation and storage, disposal and the decommissioning of waste (Poinssot et al., 2014; Norgate et al., 2014; Mallia and Lewis, 2013; Hondo, 2005). Some studies have been focused on a specific life cycle stage in isolation (Wallbridge et al., 2013; Farjana et al., 2018; Parker et al., 2016). Farjana et al. addressed the environmental impacts due to the different

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cradle-to-gate uranium mining processes, including open-pit, underground and in-site leaching (Farjana et al., 2018, 2019). Parker et al. focused on uranium mining and milling at open-pit and underground sites in Canada (Parker et al., 2016). Paulillo et al. compared the environmental impacts of reprocessing and direct disposal treatment methods of spent fuel (Paulillo et al., 2021). In another study by Wallbridge et al. the decommissioning stage was considered, with the temporary storage and spent fuel disposal steps included (Wallbridge et al., 2013).

The impact categories in the LCAs of nuclear power which have been most commonly used as the key indicators for environmental impact are GHG emissions and energy consumption, as has also been the case in other types of electricity generation (Koltun et al., 2018; Ding et al., 2017; Norgate et al., 2014; Mallia and Lewis, 2013; Hondo, 2005; Parker et al., 2016; Pomponi and Hart, 2021). A warning, however, was issued by Turconi et al. that limiting the discussion to GHG emissions and energy consumption comes with the risk of reaching a short-sighted conclusion in the life cycle environmental impacts of electricity generation (Turconi et al., 2013). It has been increasingly acknowledged that assessing a variety of different indicators is of importance for the sustainability of electricity generation (Asdrubali et al., 2015). In the LCA narratives of nuclear power, there are a number of environmental impact categories which can be considered using the International Life Cycle Data system ILCD (Farjana et al., 2018) and CML methods (Wallbridge et al., 2013), including the radioactive impacts specifically associated with nuclear power (Poinssot et al., 2014; Dungan et al., 2021).

While the environmental impact of the life cycle is a major research interest in nuclear power generation, resource-specific issues have yet to be fully discussed from the life cycle perspective. It is understood that natural resources are fundamental to human development, whereas their extraction and use is a key driver of environmental impacts (Schandl et al., 2016). In recent decades, global economic growth and overall improvements in the well-being of people almost everywhere has resulted in an acceleration of resource use, including both energy and materials (IEA, 2014). In some earlier studies, the importance of separately considering resource use and environmental impact was stressed (Hatfield-Dodds et al., 2017; Schandl et al., 2018). One of the most well-known examples is the “decoupling natural resource use and environmental impacts from economic growth” provided by the International Resource Panel of the United Nations Environment Program (UNEP, 2014). It is of paramount importance to evaluate the life cycle of nuclear power generation from the perspective that resource use is one of the origins of environmental impacts.

As such, the objective of this study is to analyze the life cycle resource use of nuclear power generation for 1 kWh based on U fuel. Both the open and closed types of fuel cycles are considered along with the three types of uranium mining methods: open-pit mining, underground mining, and in-situ leaching (ISL). Then, the difference in the environmental emissions trends is determined, and the resource use of nuclear power generation is evaluated.

This study is structured as follows. In section 2, an indicator for the natural resource use is presented. In section 3, the research boundary and the methodology of life cycle resource use of nuclear power generation are presented. In section 4, the result of life cycle resource use of U fuel cycle is presented. In section 5, uncertainty of ore grades, relationship between environmental emissions and resource use of U fuel cycle, and comparison of different power generations are discussed. This study is concluded in section 6.

## 2. Resource use measurement

### 2.1. Total material requirement

The overview of natural resource use in the LCA narrative was demonstrated in the review article by Sonderegger et al. (2020). Natural

resources are extracted through economic activity from the lithosphere, then directed to the technosphere, and finally dispersed to the ecosphere. In the flow, the extraction of a certain quantity of natural resources results in the environmental impact. In the narrative of life cycle impact analysis, various methodologies have been proposed to measure the impacts (e.g., future efforts method, depletion method, thermodynamic accounting method, and supply risk method) (Dewulf et al., 2015).

The focus in this study is the volume of natural resource extracted from the lithosphere as an input, rather than its impact in the technosphere and ecosphere as an output. This is because accounting for resource use is globally required (UNEP, 2014), as mentioned in Section 1, based on the life cycle concept.

The monitoring of the material flows associated with a process provides information which can be used to account for resource use (Baninla et al., 2019). Various indicators have been used to measure resource use, including physical material mass, intensity, and productivity (Schandl and West, 2010). The physical material mass involved in resource use is expressed in terms of different indicators, including the direct material input (DMI), raw material equivalents (RME), and the total material requirements (TMR).

Among the various indicators used to consider the physical material mass involved in resource use, TMR is considered the most encompassing. The TMR represents the direct resource (material/energy) input, indirect resource (material/energy) input and unused extraction from hidden flows (Bringezu et al., 2004). Inclusion of indirect resource used as an input as well as the hidden flows generated in the process is based on the concept of life cycle thinking. One of the particularly noteworthy aspects of TMR is that it considers mine waste, defined as the accompanied unused extractions generated through resource extraction. This mine waste is a major driver in the damage incurred by the ecosystems surrounding mining sites, and is a major contributor to the environmental impacts caused by the extraction of natural resources (Kosai and Yamasue, 2019). Given that all products have roots in natural resource extraction, it is important that the volume of ore extracted and waste rocks is considered in the hidden flow to fully understand the extraction of natural resource in the lithosphere (Nassar et al., 2022). Thus, TMR is used in this study to account for the volume of natural resource. The overview of natural resource flow in the LCA narrative and its relationship with TMR is depicted in Fig. 1.

Spanning just a few decades in the history of the narrative of the economy-wide material flow analysis, the concept of TMR has adopted for measurements of resource use for a given product in the LCA (e.g. (Kosai et al., 2021a; Watari et al., 2019; Kosai et al., 2021b),) and has gained attention as type of material footprint (Södersten et al., 2020; Wiedmann et al., 2015). In particular, in the LCA narratives of nuclear power generation, the association of energy consumption with the grade of uranium ore and type of uranium mining (e.g., open-pit and underground) is a key concern (Sovacool, 2008). Since the magnitude of mine waste through hidden flows is determined not only on the basis of ore grade but also in terms of the strip ratio, the use of TMR as an indicator of life cycle resource use is considered suitable for addressing the specific concerns associated with uranium as a resource. An overview of the TMR concept for nuclear power generation is depicted in Fig. 2.

### 2.2. TMR calculation

The key constituents of TMR are the direct volume of material (kg, L), which is the direct mass volume given in the inventory list, and the TMR volume of material (kg-TMR, L-TMR). Using these two concepts, the mining intensity, referred to hereafter as the TMR coefficient (kg-TMR/kg, L-TMR/L) is computed in the following equation.

$$\text{TMR coefficient} = \frac{\text{TMR volume}}{\text{direct volume}} \quad (1)$$

The TMR coefficient of a given product is then obtained as follows.

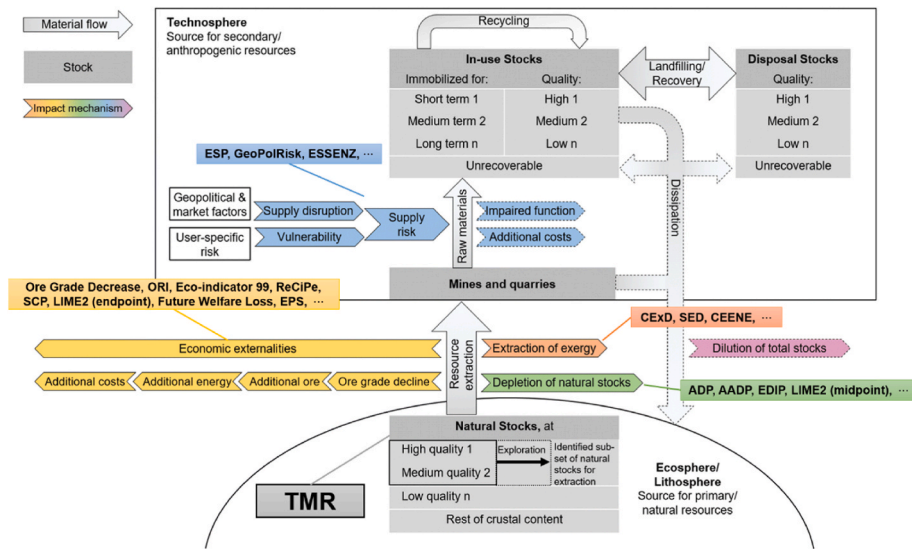


Fig. 1. Natural resource use in the LCA (Sonderegger et al., 2020) and TMR (edited by the author).

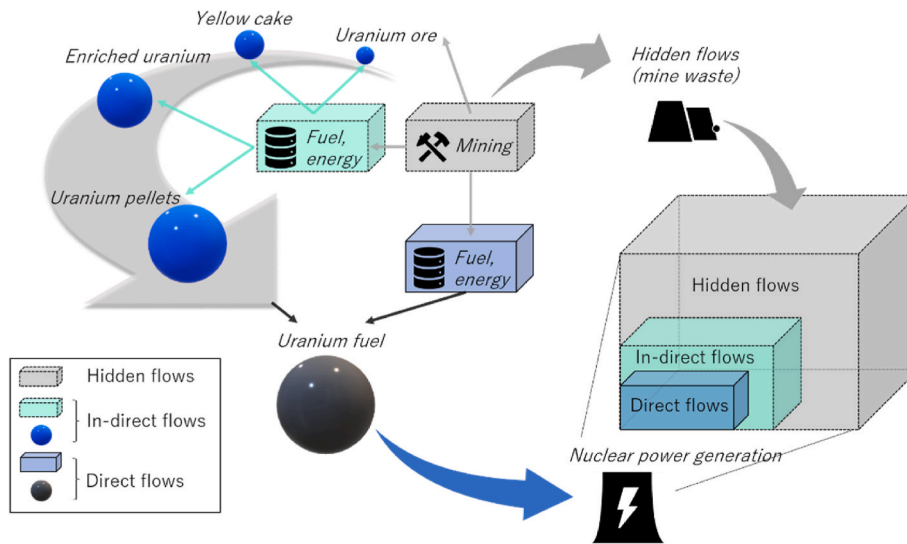


Fig. 2. Overview of TMR concept for the nuclear power generation based on the study by (Watari et al., 2019).

For a given step of processing materials, the direct volume of input materials is represented by  $A_x$ , and the direct volume of output materials is represented by  $B_y$ , where  $x$  is all input constituents and  $y$  is all output constituents. The total mass volume of all constituents of input and output are given in the following equation, respectively.

$$A = \sum A_x \tag{2}$$

$$B = \sum B_y \tag{3}$$

here, the TMR coefficient of each of input constituents is represented by  $C_x$ . The TMR volume of all input constituents, represented by  $T$ , is obtained in the following equation.

$$T = \sum A_x C_x \tag{4}$$

Following the law of conservation of mass, the gap between the TMR volume of all input constituents and the total direct volume of all output constituents is required to be properly allocated to each output constituent. Given that the product price would be an incentive of extraction, the economic allocation technique is applied, as presented in an

earlier study (e.g. (Kosai et al., 2021a)). The allocation rate, represented in the form of  $r_y$ , is obtained in the following equation.

$$r_y = \frac{B_y D_y}{\sum B_y D_y} \tag{5}$$

where, the unit price of each output constituent is represented by  $D_y$ .

Then, the TMR volume of each output constituent, expressed by  $T_y$ , is computed by the following equation.

$$T_y = (T - B)r_y + B_y \tag{6}$$

Finally, the TMR coefficient of each output component is calculated using the following equation.

$$C_y = \frac{T_y}{B_y} \tag{7}$$

$$= \left( \sum A_x C_x - \sum B_y \right) \frac{D_y}{\sum B_y D_y} + 1 \tag{8}$$

These steps for obtaining the TMR coefficient are performed sequentially for each process until attaining the target subject. It must be

noted that the TMR coefficient of natural ore (uranium), expressed by  $C_{x\_ore}$ , is represented in the following equation. Unused extraction resources from hidden flow are adequately acquired by considering the strip ratio and the ore grade in calculation process of TMR coefficient of natural ore.

$$C_{x\_ore} = \frac{1 + \text{strip ratio}}{100 \times (\text{ore grade} [\%])} \quad (9)$$

### 3. Methodology

This study aims to estimate the life cycle resource use for the nuclear power generation, considering different mining methods, power generation technologies, and uranium fuel cycles. Considering a cradle-to-grave system of each material and fuel, the inventory was collected under the International Organization for Standardization (ISO) 14040 standard (ISO and "International Standards Organization, 2006). The life cycle inventory database named ecoinvent was used in this study. The detailed data used from ecoinvent was given in each of the lifecycle stages below. The functional unit is TMR per 1 kWh through nuclear power generation. The TMR coefficient was used to estimate the resource use of nuclear power generation, referring to the aforementioned calculation process in Section 2 and the previous studies (Halada et al., 2001; Nakajima et al., 2006a, 2006b).

A brief overview of system boundary for nuclear power generation is presented in Fig. 3. The material requirement for operation and facility construction are considered at all stages. The detailed features for each of the stages are described in this section.

#### 3.1. Uranium mining & milling

The primary nuclear fuel is uranium. Uranium is distributed in the earth's crust as uranium ore. There are three major techniques for uranium mining: open-pit mining, underground mining and in-situ leaching (ISL). Those three mining methods are presented in Fig. 4. Since TMR is highly associated with mining activities, this study assesses these techniques at the uranium mining stage.

In the open-pit method, the earth's surface is drilled, blasted and excavated. A great amount of overburden, including mine waste, is extracted in the effort to extract uranium ore. In the underground method, the earth's surface is drilled to create vertical tunnels. The depth of the tunnels depends on the location of uranium deposit.

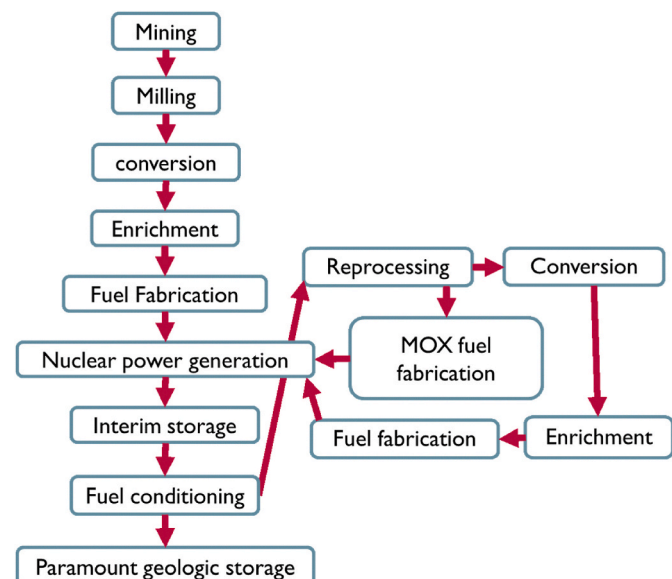


Fig. 3. System boundary for nuclear power generation.

Uranium ores obtained by the open pit and underground methods are converted to yellow-cake ( $U_3O_8$ ) after being milled with acids. In the in-situ leaching method, the earth's surface is drilled to create vertical boreholes to the depth of the shallow layer of uranium deposits. A leaching solution (e.g., sulfuric acid, nitric acid, and ammonia) is directly injected into the layer, and then the solution, which contains uranium, is pumped out (Doka, 2011). Yellow-cake ( $U_3O_8$ ) is produced from this solution.

The ore grade and strip ratio of each mining method used in this study is summarized in Table 1. These values are mainly based on the ecoinvent representative data. The uncertainty of ore grade in each mining method is further discussed in Section 5.1. The material requirement for mining and milling is presented in appendices A-1 and A-2.

#### 3.2. Uranium conversion

In the uranium conversion process,  $U_3O_8$  is converted to  $UF_6$  using one of two methods: a dry process and a wet process. In the dry process, not only  $UF_6$  but also liquid fluorine, sulfur hexafluoride, antimony pentafluoride, iodine pentafluoride are produced as the byproducts. It should be noted that these byproducts are not considered in this study since no inventory data for them is available. In this study, it is assumed that the rate of use of both methods is the same: the dry process at 50% and the wet process at 50%. The material requirement for conversion is presented in appendix A-3.

#### 3.3. Uranium enrichment

$UF_6$  contains the uranium isotopes U-235 (approximately 0.7%). It needs to be enriched to 3–5% to be used as the fuel for nuclear power generation. There are two methods for enrichment: diffusion and centrifuging. Since the energy efficiency of centrifuging is higher than that of diffusion, centrifuging is the main method used (Dones et al., 2012). Centrifuging was therefore adopted as the enrichment method in this study. The material requirement for enrichment is presented in appendix A-4.

#### 3.4. Fuel fabrication

Uranium pellets are fabricated in a heating process at high temperature after the enriched uranium is converted to pulverized  $UO_2$ . The obtained pellets are arranged in a zirconium cladding fuel rod. The fuel assembly is composed of a thermometer and control rods to control the value of neutron 264 fuel rods and 320 uranium pellets. The material requirement for fuel fabrication is presented in appendices A-5 and A-6.

#### 3.5. Nuclear power generation

##### 3.5.1. Plant construction

Nuclear power plants have either a "Boiling Water Reactor (BWR)" or a "Pressure Water Reactor (PWR)". In the BWR, the reactor core directly boils water, which turns to steam and then drives a turbine. In the case of the PWR, the reactor core heats water and the hot water exchanges heat with the system of lower pressure water, which turns to steam and then drives a turbine. In this study, both types of nuclear power plants were assessed. The material requirement for nuclear power plants and their operation is presented in appendices A-7 and A-8.

##### 3.5.2. Operation

The nuclear fuel cycle is generally classified into two types: the "open" fuel cycle and the "closed" fuel cycle. Conventional nuclear reactors have an "open" fuel cycle, with the spent fuel directly channeled to disposal. Reactors with a "closed" fuel cycle extract the fissionable materials from spent fuels to be recycled as fuel, with some additional phases (fuel conditioning, reprocessing, enrichment, reconversion and

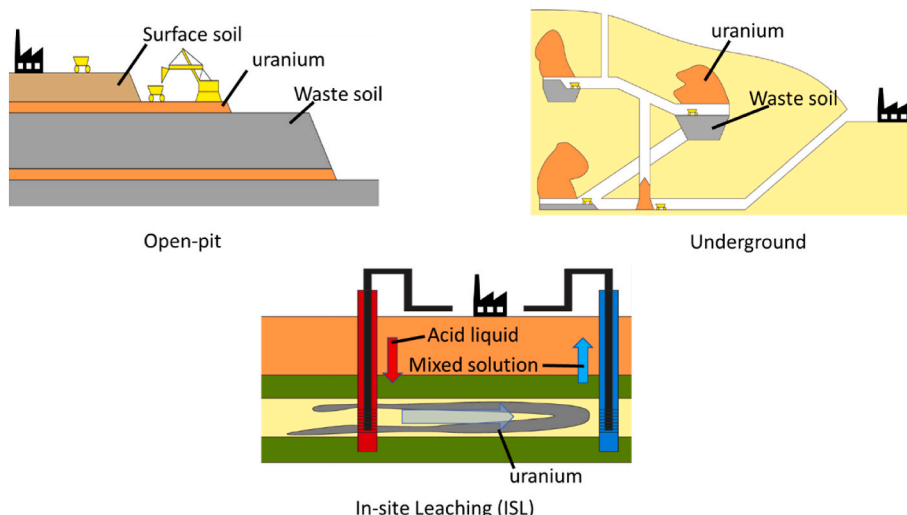


Fig. 4. Methods of excavation.

**Table 1**  
Ore grade and strip ratios.

Mining method	Ore grade [%]	Strip ratio	Reference
Open-pit	0.127	15	Dones et al. (2009a)
Underground	0.172	1	Dones et al. (2009a)
In-situ leaching	0.168	0.62 <sup>a</sup>	(Doka, 2011) (IAEA, 2001) (U.S. Energy Information Administration, 2019)

<sup>a</sup> This value was calculated using borehole dimensions.

fuel fabrication). The “closed” fuel cycle is further demonstrated in Section 3.7 and Section 3.8.

### 3.6. Interim storage

In this stage, the spent fuel is delivered to the interim storage and stored in the storage pool until the radiation intensity reaches an acceptable level. In general, the storage canister is temporarily sealed and stored for 5–7 years until the rate of decay and the temperature falls below the maximum threshold (Dones et al., 2009b). Depending on the possibility of fission, the spent fuel after the interim storage is channeled to two streams: reprocessing (Section 3.1.8) or encapsulation for long term storage (Section 3.1.9) (Svensk Kärnbränslehantering, 2010a).

### 3.7. Fuel conditioning

In this stage, the spent fuel is assorted to the nuclear fission products and the undissolved residue. The spent fuel is finely sheared after interim storage, dissolved by nitric acid (HNO<sub>3</sub>), and then classified to nuclear fission products containing dioxide uranium (UO<sub>2</sub>) and dioxide plutonium (PuO<sub>2</sub>) and undissolved residue. The nuclear fission products are transferred to the reprocessing stage, while the undissolved residue is chemically treated to form vitrified waste (Ojima, 2008).

### 3.8. Reprocess

In this process, the uranium (U-235, U-238) and plutonium reclaimed from spent fuel are reconverted to reprocessed uranium fuel and Mixed Oxide fuel (MOX fuel) (Dones et al., 2009b). The detailed process of producing reprocessed uranium fuel and MOX fuel is presented below.

Approximately 1% of the U-238 contained in the uranium fuel is

converted to plutonium as a byproduct of the reactions of the uranium fuel in the reactor. The spent fuel is composed of approximately 1% U-235, 1% plutonium, 3–5% fission products and 93–95% non-fissile uranium (U-238) (Kansai Electric Power). From 1 kg of spent fuel, 0.92 kg of uranium and 0.01 kg of plutonium is extracted using nitric acid and oily solutions. These are reprocessed because of their reusability as fuel.

After the reprocessed uranium fuel is converted to UF<sub>6</sub> and enriched, it is reconverted to UO<sub>2</sub> and channeled to fuel fabrication. In this study, the inventory data of the process of conversion, enrichment and fuel fabrication for the “open” fuel cycle (Dones et al., 2009b) are included in these processes under reprocessing. The relevant inventory data are presented in appendix A-8, appendix A-9, and appendix A-10.

The mixture of dioxide-uranium from both the spent fuel and open cycle and plutonium obtained from the spent fuel are channeled to the MOX fabrication facility. The MOX fuel is composed of 4–9% plutonium and 91–96% U-238 (Japan Nuclear Fuel Limited). The inventory data for the facility of MOX fuel fabrication is the same as that for the “open” fuel cycle. This inventory data is presented in appendix A-11.

### 3.9. Paramount geologic storage

In the disposal stage, the spent fuel is stored for the long term once the level of radioactivity is reduced to the required level during the interim storage stage. As yet, no country has ever adopted the paramount geologic storage concept (WNWR, 2019). Therefore, in this study, the estimated data produced in Sweden (Svensk Kärnbränslehantering, 2010b) is used. The spent fuel is stored inside a cylinder made of nodular cast iron, called an insert. Copper is used in the shell to cover the insert, and the shell with an insert is called a canister. The differences between the PWR and BWR inserts are shown in Fig. 5. According to a Swedish report (Svensk Kärnbränslehantering, 2010b), it is possible to store 4451 BWR canisters and 1652 PWR canisters in the storage facility. According to an estimate in the report, a total of 6103 canisters have been transferred to the underground facility, and they will need to remain there for more than 100 thousand years until radiation levels fall below a threshold considered safe. In this study, the amount of land disturbed for the construction of underground facilities is also considered mine waste, with the relevant data taken from the Swedish report (Svensk Kärnbränslehantering, 2010b). The material requirement for paramount geologic storage is presented in appendix A-12.

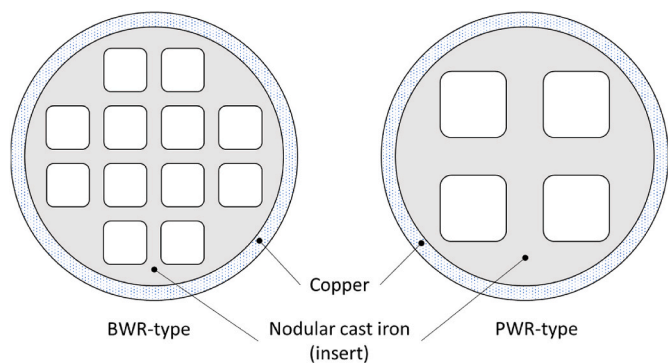


Fig. 5. Difference between the BRW and PWR canisters.

3.10. TMR assessment

The TMR coefficient of uranium fuels per kg, including yellow-cake (U<sub>3</sub>O<sub>8</sub>), enriched uranium (UF<sub>6</sub>), nuclear fuel (UO<sub>2</sub>), MOX fuel, and reprocessed uranium fuel, was first calculated based on Section 2. These are expressed in the form of kg-TMR/kg. Then, the TMR coefficient of nuclear power generation per kWh was also calculated. The TMR coefficient of all input materials is represented in appendix A-9, and the details of calculation for the TMR coefficient of uranium fuels (kg-TMR/kg) and the TMR coefficient of nuclear power generation are provided in appendix A-13.

4. Results

4.1. TMR of uranium fuel

The TMR coefficient of each 1 kg of uranium fuel, MOX fuel, and reprocessed uranium fuel used for nuclear power generation for the different mining methods is provided in Fig. 6.

While the overall trend in the TMR coefficient of uranium fuels was found to be the same regardless of the mining method, the TMR decreased in the following order: uranium fuel (UO<sub>2</sub>), reprocessed uranium fuel, and MOX fuel.

The TMR coefficient of uranium fuel was shown to increase significantly by enriching yellow-cake (U<sub>3</sub>O<sub>8</sub>). This is because 8.31 kg of yellow-cake (U<sub>3</sub>O<sub>8</sub>) is required to produce 1 kg of enriched uranium (UF<sub>6</sub>). Although the conversion of uranium fuel from UF<sub>6</sub> to UO<sub>2</sub> has little impact on the TMR coefficient of uranium fuel, it decreases by approximately 50% as a result of fuel fabrication due to the limited number of nuclear fuel pellets (UO<sub>2</sub>) inserted in the fuel rods assembly. The difference in the TMR coefficient of MOX fuel and reprocessed uranium fuel is due to the difference in the price of the fuel.

Despite the same trend in magnitude correlation among uranium

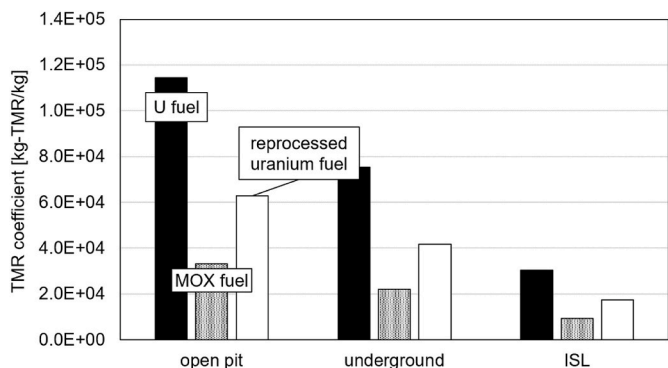


Fig. 6. TMR coefficient of production of uranium fuel, MOX fuel, and reprocessed uranium fuel.

fuels, the TMR coefficient of each uranium fuel differed significantly depending on the mining method. Based on the ecoinvent data used in this study, there was a decrease in the TMR coefficient of each uranium fuel in the following order: open pit, underground, and ISL. The difference can be attributed to the different ore grade and strip ratio of the three mining methods: both of these factors impact the TMR coefficient of yellow-cake (U<sub>3</sub>O<sub>8</sub>) during the mining and milling stages. Notably, the inventory data per unit of all stages except for mining and milling was found to be the same regardless of the mining method. The effect of the change in the TMR coefficient of yellow-cake (U<sub>3</sub>O<sub>8</sub>) on other uranium fuels was considerable.

4.2. Comparison between PWR and BWR

The TMR coefficient of nuclear power generation is shown in Fig. 7. The TMR coefficient of the PWR of the open cycle system using open pit mines is the highest, while that of the PWR and BWR of the closed cycle system using ISL is the lowest.

To generalize, there is almost no difference in the TMR coefficient of PWR and BWR in the open cycle and closed cycle systems. The TMR at the power generation stage of PWR and BWR, however, were shown to differ slightly. The fuel requirements for the production of electricity were found to be almost the same, while the material requirement for the production of electricity using the BWR was found to be greater than that for the PWR. This causes a slightly higher TMR coefficient for the BWR at the power generation stage, which is a negligible considering all of the stages in the life cycle.

The TMR coefficient of the mining methods was shown to decrease in the following order: open pit mining, underground mining and ISL. The difference in the TMR coefficient of open pit mining and ISL was considerable. The difference in the ore grade and strip ratio had a strong impact on the outcome, as mentioned in Fig. 6.

4.3. Configuration

A detailed configuration of the TMR coefficient of open pit mining, underground mining and ISL is provided in Fig. 8. Since the configuration of the TMR coefficient of open pit mining and underground mining was almost the same, the case of open pit mining is demonstrated here.

In general terms, the stages of mining, conversion and power generation are the dominant factors in the TMR coefficient regardless of the mining method and recycling system. The impact of the other stages, including enrichment, fuel fabrication, interim storage, fuel conditioning and paramount geologic storage on the outcomes was not significant.

Note that even when the dominant stages of open pit mining and ISL

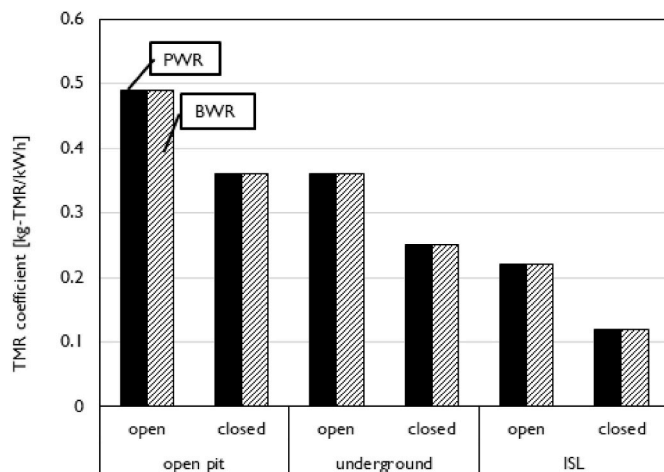


Fig. 7. TMR coefficient of nuclear power generation.

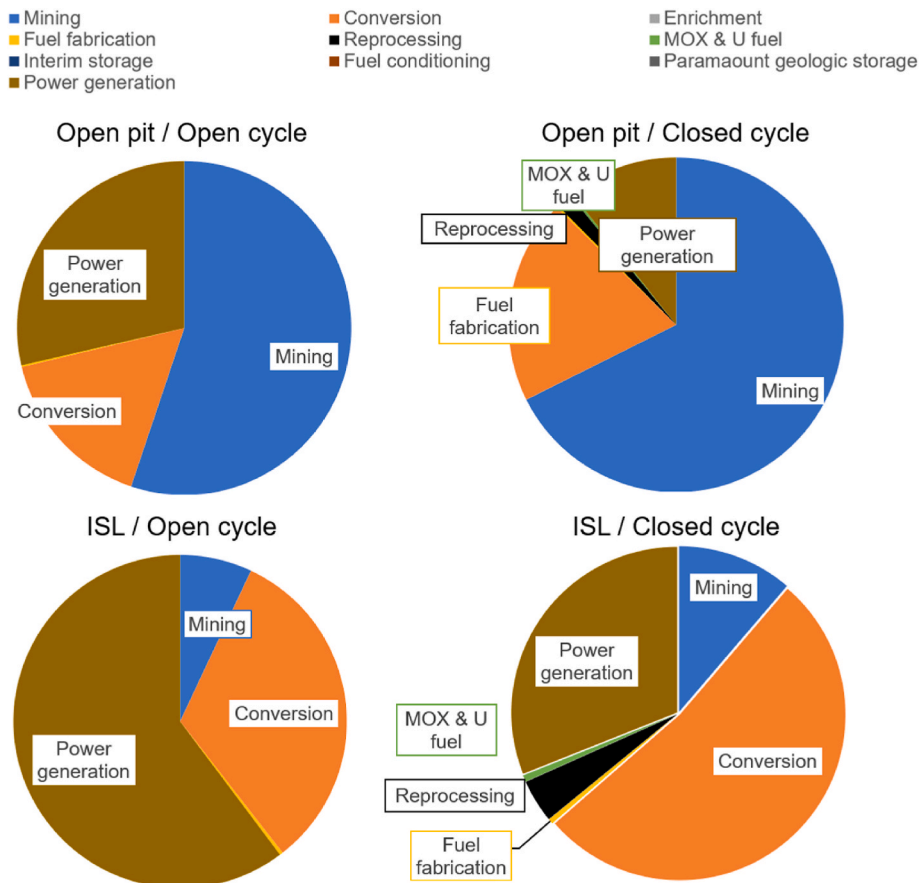


Fig. 8. Configuration of the TMR coefficient.

are the same, the share of each stage in the TMR is remarkably different. In the case of open pit mining, approximately 60% of the contribution to the TMR is the open pit mining process itself, whereas the contribution of ISL to the TMR is approximately 10%. This difference can be attributed to the lower ore grade of open pit mining than that of ISL, as well as to the strip ratio.

A common feature of open-pit mines, underground mines and ISL is that the relationship between the share of the stage of mining and conversion for the open cycle method is the same as that for the closed cycle method, whereas the share of power generation for the open cycle method is greater than that for the closed cycle. This is because the closed method requires less material per 1 kWh of the facility for power generation. Also, a light contribution is made by the reprocessing stage. Since the spent fuel is the dominant factor in the TMR coefficient of reprocessing, the calculations are greatly affected by earlier stages, such as conversion and mining.

## 5. Discussion

### 5.1. Uncertainty of ore grade

In earlier studies, such contextual factors as uranium enrichment method, country-specific electricity configuration, and uranium ore grade were considered the large contributors to variations in the estimates of life cycle (Warner and Heath, 2012; Fthenakis and Kim, 2007; Sovacool, 2008). It must be understood that the uncertainty regarding changes in the grade of uranium ore has a potentially large impact on the TMR calculations. Therefore, a sensitivity analysis was performed to evaluate the influence of the uncertain grade of uranium ore on the calculated TMR coefficient of nuclear power generation.

The data for the grade of uranium ore for each mining method was

taken from the report by Nuclear Energy Agency and International Atomic Energy Agency (Nuclear Energy Agency and International Atomic Energy Agency, 2018), National Research Council (National Research Council, 2012), Zurich (Doka, 2011), and Parker et al. (2016), as presented in Appendix B.1. Based on the various ore grades collected, variations in the grade of uranium ore are shown in Fig. 9. The uranium ore grade distribution ranged from 0.015% to 0.3% for the three types of mining methods.

The TMR coefficient of nuclear power generation based on the ecoinvent data as representative data is presented in Fig. 10. The error range for the variations in the grade of uranium ore is also included.

The grade of uranium ore is lower than that of other metallic ores (Ni; 0.9%, Cu; approximately 0.7%, Fe; approximately 60%, Al; approximately 40% (Ame Research, 2018) (Ame Research, 2015)), and the TMR coefficient of nuclear power generation increases when the

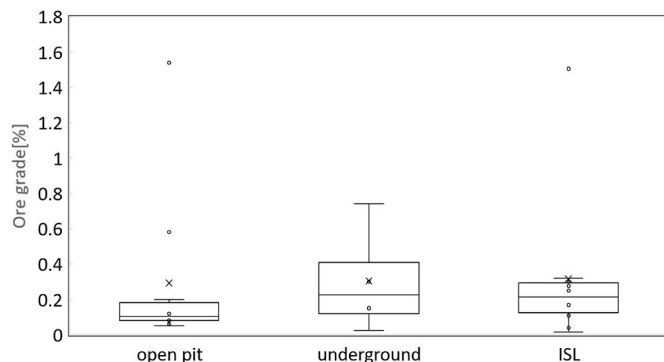


Fig. 9. Distribution of the uranium ore grade.

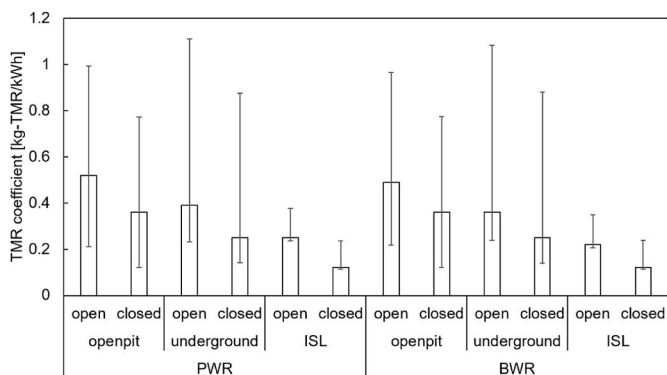


Fig. 10. Uncertainty in the TMR coefficient of nuclear power generation considering variations in the grade of uranium ore.

grade of the uranium ore is lower. In fact, the TMR coefficient based on the ecoinvent data as representative data is relatively low and within the error range of ore grade uncertainty. Even though the widest distribution of ore grade among the collected data was for ISL, the TMR coefficient of nuclear power generation based on open pit mining and underground mining is greater than that of ISL, as shown in Fig. 9. This is because the contribution from the mining stage to the outcome of the TMR assessment is more significant in the case of open pit mining and underground mining than that of ISL. The TMR values calculated in this study suggest that in the development of uranium deposits, it is important to take the grade of the ore into account when deciding upon open pit or underground mining methods rather than ISL. In the case of lower grades of ore, these methods would be inferior to ISL in terms of TMR.

The ISL technique has become increasingly common over the last 20 years. Today, 57% of uranium ore is mined using ISL because it is considered cost effective and its environmental impact (WNA, 2020) is lower than that of conventional mining methods. This trend also has advantages in terms of TMR. However, there are several concerns in the ISL process. To some extent, the applicability of ISL depends on the topography of the deposit because the ore body needs to be permeable and to be sandwiched by an impermeable stratum. In addition, the injection of the acid or alkali liquid to the underground situ inevitably pollutes the surrounding environment. Hence, this mining method cannot be considered applicable to all deposits. As such, it is important to consider various perspectives, such as the TMR, when selecting the mining method.

5.2. Relationship between GWP and TMR

The evaluation of the global warming potential (GWP) is almost universally considered the most important factor in assessing the environmental impact of nuclear power generation (Koltun et al., 2018; Ashley et al., 2015). Evaluations of the resource usage, however, are sorely missing in considering the environmental impact of generating power in this way. Therefore, it is important to explore the relation between TMR and GWP and to determine the optimal balance in the environmental impacts, including the resource use, in nuclear power generation.

A comparison of the GWP and TMR at the stage of mining for uranium is presented in Fig. 11. The GWP data is taken from the report by Ashley et al. (2015). The trends for the GWP and TMR at the mining stage differ remarkably. The GWP at the mining stage decreases in the following order: underground mining, ISL and open pit mining. Note that the GWP of ISL and open pit mining is almost the same. Meanwhile, the TMR coefficient at the stage of mining decreases in the following order: open pit mining, underground mining, ISL for uranium mining. In addition, the variation of TMR (CV: coefficient of variation = 0.69) is

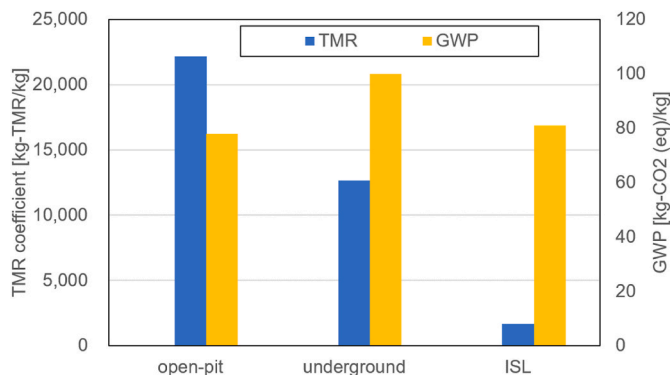


Fig. 11. Comparison of GWP and TMR at the mining stage.

significantly greater than that of GWP (CV = 0.11), which means that the resource use is more largely affected by mining method.

The different trends in the GWP and TMR of nuclear power generation considering the mining method suggest that it is necessary to reconsider the evaluation framework for power generation. The heavy reliance on greenhouse gas emissions and global warming potential when evaluating the environmental impact of power generation technologies comes at significant risk. Despite the undeniable importance of these factors, this conventional approach for evaluating the environmental performance of power generation may lead to hidden factors associated with natural resource use being completely overlooked.

5.3. Comparison of nuclear power generation with others

This study has explored the resource use of nuclear power generation. Is it higher or lower than that of other power generation sources? Although no detailed calculations of the TMR coefficients of other power generation methods have been conducted, the TMR coefficient of various types of power generation can be compared using approximate estimates (NIMS, 2009; Central Research Institute of Electric Power Industry, 2016). The representative value of the TMR coefficient of nuclear power generation was determined based on the following assumptions: 25% open pit, 25% underground, and 50% ISL, with 50% open cycle and 50% closed cycle (Ashley et al., 2015).

As shown in Fig. 12, the TMR coefficient of nuclear power generation is lower than that of thermal power generation (e.g., approximately 20% that of coal power generation, 23% that of oil power generation, and 35% that of liquified natural gas power generation) and is similar to renewables, such as the power generated by solar photovoltaic cells.

While the resource intensity of the uranium fuel is significantly high, as shown in Fig. 6, the high energy density is the major contributing factor in categorizing nuclear power generation in the lower TMR

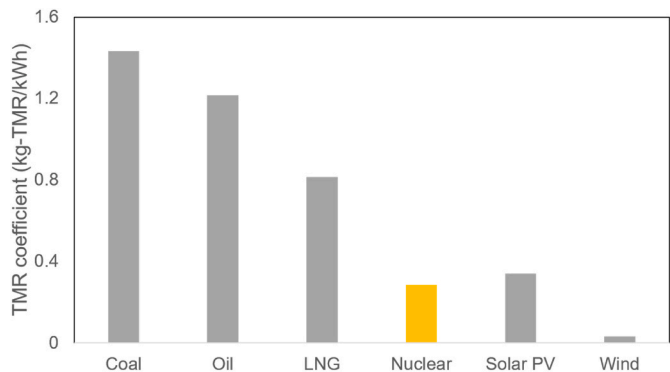


Fig. 12. Comparison of TMR coefficient between nuclear and other power sources.

coefficient group.

There are various issues associated with nuclear power use, including the waste treatment of spent fuel, public acceptance, severe accidents, and nuclear proliferation. However, the various advantages of nuclear power, and particularly its low emissions of greenhouse gases, overcome these considerable disadvantages in the minds of many. Through the analysis in this study, it could be said that nuclear power generation is favorable from the perspective of not only global warming, as is widely understood, but also natural resource use in the LCA narrative.

In this study, the focus is on the uranium fuel cycle as a basis of nuclear power generation. However, new fuel cycles have been proposed to effectively use resources, such as the thorium-uranium fuel cycle. Thus, the exploration of resource use in various fuel cycles of nuclear power generation is required in future studies.

## 6. Conclusion

In this study, the life cycle resource use of nuclear power generation was analyzed using the concept of TMR. In the analysis, the focus was on the mining methods, the reactor types, and the type of fuel cycle system employed (open or closed). The uncertainty of the grade of the uranium ore was also evaluated. Finally, the relationship between the GWP and TMR was considered, and a comparison was made between nuclear power generation and other types of power generation systems.

The major findings are as follows:

- The TMR coefficient of uranium fuels decreases in the following order: enriched uranium (UF<sub>6</sub>), nuclear fuel (UO<sub>2</sub>), reprocessed uranium fuel, MOX fuel and yellow-cake (U<sub>3</sub>O<sub>8</sub>).
- The value of the TMR coefficient for the uranium fuel varies significantly depending on the grade of the ore and the strip ratio corresponding to the various mining methods.
- There is almost no difference in the TMR coefficient of PWR and BWR in the open cycle and closed cycle.
- The stages of mining, conversion and power generation are the dominant factors in the TMR coefficient regardless of the mining method and the method employed for fuel recycling.
- The trends in the GWP and TMR of nuclear power generation differ considerably according to the mining method. The resource use rather than greenhouse gas emissions is more largely affected by mining method.
- The TMR of nuclear power generation is significantly lower than that of thermal power generation and is similar to that of renewables. On the basis of the low greenhouse gas emissions associated with nuclear power generation, like renewables, it can be considered favorable not only from the global warming perspective but also from a resource use perspective.

## CRedit authorship contribution statement

**Nanami Nakagawa:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing. **Shoki Kosai:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing. **Eiji Yamasue:** Conceptualization, Investigation, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2022.132530>.

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