Life Cycle Assessment (LCA) of Nuclear Power in Switzerland

Final Report

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Jost Eikenberg: front-end nuclear fuel cycle

Responsibilities, liability and funding of this study

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Acronyms

Acronyms	Full Name
BWR	Boiling Water Reactor
GHG	Greenhouse Gas
ISL	In-situ Leaching
KKL	Kernkraftwerk Leibstadt
KKG	Kernkraftwerk Gösgen
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PSI	Paul Scherrer Institut
PWR	Pressurized Water Reactor
MWd	Megawatt days
ILCD	International Reference Life Cycle Data System

Summary

This report serves as documentation of the most recent Life Cycle Assessment (LCA) of nuclear power in Switzerland, which was carried out by PSI on behalf of swissnuclear.

Life Cycle Assessment is used as methodology for the quantification of complete environmental burdens and potential impacts of products and services along their entire life cycle. In case of nuclear power in Switzerland, this means that the environmental burdens per kilowatt-hour of electricity generated are quantified. The nuclear power plants in Gösgen (KKG) and Leibstadt (KKL) are analyzed.[1] Environmental burdens cover emissions to air, water bodies and soil, extraction of resources as well as land use. The LCA covers the complete so-called "nuclear energy chain", including uranium mining and milling, conversion and enrichment, fuel element fabrication, power plant construction, operation and decommissioning as well as geological storage of radioactive waste. The LCA of KKG analyzed the environmental burdens of electricity from pressurized water reactors (PWR), and the LCA of KKL analyzed the environmental burdens of electricity from boiling water reactors (BWR).

This analysis represents a substantial update and extension of the previous LCA of nuclear power in Switzerland. Inventory data of all processes of the nuclear chain have been updated in close collaboration with the plant operators and the responsibles for fuel supply; furthermore, some new processes were integrated, e.g. for the decommissioning of the power plants at the end of their lifetimes. Hence, this LCA contains the latest inventory data for nuclear power in Switzerland based on accessible data. Data quality can be rated as good for most processes. Some processes, which had to be updated based on literature only, are of acceptable quality. Only uranium extraction and processing for fuel element fabrication in Russia, which is a relevant part of the fuel supply for KKL, is partially of insufficient data quality. An (unknown) fraction of this uranium originates from disarmed nuclear weapons – complete data for the associated processes are not available to the authors of this report.

The following environmental indicators were quantified: Greenhouse Gas (GHG) emissions as measure for impacts on climate change; ionizing radiation; particulate matter formation (primary and secondary); land use; acidification; freshwater ecotoxicity; human toxicity. Extensive sensitivity analyses have been carried out in order to estimate the sensitivity and variability of the LCA results. These concern three aspects: modeling of the nuclear power generation chain, the reference time frame used in compiling the inventory data, and ranges of raw data which were used for establishing process inventories. The assumptions taken for modeling of the nuclear power generation chain turn out to be most important regarding sensitivity and variability of LCA results.

[1] Reasons for this selection are the following: two single-unit power plants together contribute about two thirds to Swiss nuclear generation; they have been built most recently, have the largest capacities in Switzerland and are supposed to be operated much longer than the other three smaller reactors.

The LCA results show that the origin of uranium represents the dominating factor concerning the environmental performance of Swiss nuclear power. Most important in this context are uranium concentrations as well as technologies and energy carriers used to mine and process the uranium resources. A large fraction of environmental burdens is caused by the tailings of uranium mining and milling and the quantity of these tailings increases with decreasing ore grades. The burdens due to uranium enrichment have decreased compared to previous LCA of Swiss nuclear power, since today, fuel is entirely enriched with centrifuge technology, which is much less energy intensive than the previously (partially) used diffusion technology.

LCA results of Swiss nuclear power are – compared to other electricity generation technologies (hydro, wind and solar power, natural gas and coal power plants) – quite good. For most of the environmental indicators, results for nuclear power are in the low or middle range among the technology-specific burdens, except ionizing radiation, which is significantly higher for nuclear power than for other technologies. Nuclear power exhibits very low GHG emissions, only slightly higher than those of hydro power in Switzerland, which represents the most climate-friendly technology.

Future work in the area of LCA of Swiss nuclear power should focus on refining the data of fuel supply and processing. Data quality of these processes is currently partially insufficient, and these processes are of great importance in the overall LCA of nuclear power. Hence, these current data gaps trigger high uncertainties of results.

Zusammenfassung

Dieser Bericht dokumentiert die neueste Ökobilanz der Kernenergie in der Schweiz, die vom PSI im Auftrag von swissnuclear erstellt wurde.

Mit einer Ökobilanz (englisch: "Life Cycle Assessment" – LCA) werden die gesamten Umweltauswirkungen von Produkten entlang ihres Lebensweges quantifiziert. Im Fall der Schweizer Kernenergie bedeutet dies, dass die Umweltauswirkungen pro Kilowattstunde Strom, der in den beiden Kernkraftwerken Gösgen (KKG) und Leibstadt (KKL) produziert wird, berechnet werden.[2] Unter Umweltauswirkungen fallen Schadstoffemissionen in Luft, Boden und Gewässer, der Verbrauch an Ressourcen sowie Landfläche. Die Ökobilanz deckt die gesamte so genannte "Kernenergiekette" ab, von der Urangewinnung und -aufbereitung über Anreicherung, Herstellung der Brennelemente, Bau, Betrieb und Rückbau der Kraftwerke bis zur Endlagerung der radioaktiven Abfälle. Die Bilanz für den Strom aus dem KKG repräsentiert Druckwasserreaktoren (DWR), jene für den Strom aus dem KKL Siedewasserreaktoren (SWR).

Diese Arbeit stellt eine Aktualisierung und Erweiterung der bisherigen Ökobilanzen der Kernenergie in der Schweiz dar. In Zusammenarbeit mit den Betreibern der Kraftwerke und den Verantwortlichen für die Brennstoffversorgung wurden die Inventardaten sämtlicher Prozesse aktualisiert; weiter konnten Inventardaten für bisher fehlende Prozesse erstellt werden, z.B. für den Rückbau der Reaktoren am Ende der Lebensdauer. Somit enthält diese Ökobilanz den neuesten Datenbestand für Kernenergie in der Schweiz anhand der den Autoren zugänglichen Informationen. Die Datenqualität kann zu einem grossen Teil als gut bezeichnet werden. Für einige Prozesse, die nur auf Literatur basierend aktualisiert werden mussten, ist die Datenqualität akzeptabel. Lediglich die Urangewinnung, -aufbereitung und -verarbeitung zu Brennelementen in Russland, welche für die Brennstoffversorgung des KKL relevant ist, konnte nicht zufriedenstellend bilanziert werden. Ein (unbekannter) Teil des Urans stammt hier aus abgerüsteten Kernwaffen und für die damit verbundenen Prozesse sind keine vollständigen Informationen verfügbar.

Folgende Umweltindikatoren wurden berechnet: Treibhausgasemissionen als Mass für den Beitrag zum Klimawandel; radioaktive Strahlung; Bildung von primären und sekundären Aerosolen (Partikeln); Landnutzung; Versauerung; Ökotoxizität in Gewässern; toxische Wirkungen für den Menschen. Um die mögliche Sensitivität und Variabilität der Ökobilanz-Ergebnisse abzubilden, wurden Sensitivitätsanalysen durchgeführt. Diese betreffen drei Faktoren: die Modellierung der Kernenergiekette, den für die Erstellung der Inventardaten massgeblichen Betrachtungszeitraum und die Bandbreiten der Originaldaten, welche zur Erstellung der Inventardaten genutzt wurden. Als wichtigster Faktor wurden die Annahmen in der Modellierung der Kernenergiekette identifiziert.

[2] Gründe für die Auswahl sind die folgenden: KKG und KKL tragen etwa zwei Drittel zur heutigen Stromproduktion der Schweizer Kernkraftwerke bei. Es sind auch die jüngsten Anlagen mit der höchsten Leistung in der Schweiz, die aller Voraussicht nach am längsten betrieben werden.

Die Ökobilanz-Ergebnisse zeigen, dass die Herkunft des Urans den grössten Einfluss auf die Umweltauswirkungen des Stroms aus Kernkraftwerken (KKW) aufweist. Die entscheidenden Faktoren sind einerseits die Urankonzentration bei der Gewinnung der Ressourcen, andererseits die Technologien und Energieträger, die für die Gewinnung und Verarbeitung der Ressourcen verwendet werden. Ein grosser Teil der Umweltauswirkungen wird von den Rückständen der Urangewinnung verursacht, deren Mengen mit abnehmender Urankonzentration steigen. Im Vergleich zu früheren Ökobilanzen haben die Umweltbelastungen aus der Urananreicherung abgenommen, da der Brennstoff für die Schweiz mittlerweile ausschliesslich mit Zentrifugen angereichert wird, welche deutlich weniger Strom benötigen als die früher (auch) genutzten Diffusionsverfahren.

Im Vergleich zu anderen Technologien zur Stromproduktion (Wind- und Wasserkraft, Fotovoltaik, Erdgas- und Kohlekraftwerke) sind die Ökobilanzergebnisse des Stroms aus den Schweizer Kernkraftwerken relativ gut. Bei den meisten Umweltindikatoren liegt der Strom aus den KKW im unteren bis mittleren Bereich des Spektrums der technologiespezifischen Umweltauswirkungen. Ausnahme ist die radioaktive Strahlung – davon verursacht die Kernenergiekette mit Abstand am meisten. Bezüglich Treibhausgasemissionen schneidet Strom aus Schweizer KKW sehr gut ab, lediglich Strom aus Wasserkraftwerken ist klimafreundlicher.

Zukünftige Arbeiten im Bereich „Ökobilanz der Schweizer Kernenergie“ sollten ihr Augenmerk vor allem auf die Urangewinnung und -aufbereitung und die damit verbundenen Prozesse legen. Hier ist einerseits die Datenverfügbarkeit momentan zum Teil schlecht, andererseits sind die Unsicherheiten hoch und ebenso die Auswirkungen auf die Ökobilanzergebnisse der Kernenergie insgesamt.

1. Introduction

Nuclear power has contributed about 38% of the total electricity production in Switzerland in the past decade (BFE, 2014), making it an essential part of Swiss electricity supply. However, following the nuclear accident in Fukushima in Japan, the Swiss Federal Council and parliament decided that the five nuclear power plants in Switzerland would be decommissioned when they reach the end of their service life and no new nuclear power plants would be built. But the operations of the existing Swiss nuclear power plants are still on a long-term basis, and even in case of no more new nuclear power plants being built in the future, state-of-the-art Life Cycle Assessment (LCA) of nuclear power in Switzerland needs to be provided in order to evaluate its environmental performance; not only from current but also future perspective, considering the long-term time horizon, and potential operation and performance of nuclear reactors in Switzerland.

The acceptance of nuclear power generation depends – among other factors – on its environmental performance in comparison to other electricity generation technologies. Life Cycle Assessment (LCA) is a comprehensive method that allows for such evaluation and comparison on the basis of consistent system boundaries and complete coverage of the lifecycle of electricity generation. Previously available Life Cycle Inventory (LCI) data and Life Cycle Impact Assessment (LCIA) of nuclear power generation in Switzerland were partially outdated, and did not appropriately reflect current and future Swiss specific boundary conditions; inventory data representing prospective future technologies for the nuclear fuel cycle were not available making it a challenge to estimate the present and potential future trend of environmental performance of Swiss nuclear power.

The main objective of this project was the update and extension of LCI data of nuclear power generation, and the development of prospective LCI for future Swiss nuclear power generation. The project was officially started in the beginning of 2014. However, the actual collection of data could not be initiated until late August 2014, due to time spent on obtaining administrative approvals. With the close collaboration between PSI and data providers from Axpo, Nuclear Power Plant Gösgen (KKG) and Nuclear Power Plant Leibstadt (KKL), updated information for many parts of the entire nuclear fuel cycles for these plants was collected, including front-end uranium mining and processing, fuel production, nuclear power plant operation, as well as the back-end nuclear waste processing and the plant decommissioning.

This report will first explain the methodology of the study, including scope and system boundaries, and the selection of LCIA methods. It will be followed by a summary of LCI updates, potential future operation and performance advance by process, the quality of data as well as main references and assumptions used to derive the LCI data. Potential environmental impacts of nuclear power generation (i.e. LCIA results) based on the updated inventory data is then presented, with contribution by process of the nuclear cycle; these impacts are compared to other electricity generation technologies on the basis of 1 kWh electricity generation. Due to the relative major contribution of uranium mining to most of the environmental impacts and the partially unknown origin of uranium for fuel supply of KKL, a closer look was taken into the process of uranium mining: country-specific uranium mining activities are compared in terms of their environmental burdens. Sensitivity analysis is performed considering both modeling and data uncertainties and variability; furthermore, two sets of inventory data derived from different time frames for KKL are evaluated. In the end, prospective scenarios of Swiss nuclear power are presented, together with their environmental impacts.

It needs to be noted that data availability concerning a substantial fraction of uranium supply for the KKL (BWR) NPP is limited, and as a consequence, the associated uncertainties in the LCA results for this NPP are high and results need to be interpreted with caution.

2. Methodology

2.1. Goal, scope and system boundary

The goal of this work is to evaluate the environmental burdens and potential impacts of the current (as of 2017 and from thereon) nuclear power generation in Switzerland, represented by the two largest nuclear power plants in Gösgen and Leibstadt and their associated fuel supply chains. In addition, future potential changes concerning plant operation and fuel supply and the associated environmental burdens and potential impacts are analyzed. Life Cycle Assessment methodology is applied for this evaluation. The LCA is carried out as process-based and attributional analysis (Earles & Halog, 2011; Zamagni, Guinée, Heijungs, Masoni, & Raggi, 2012). ecoinvent version 3.3 data (ecoinvent, 2016) have been mainly used as background LCI[3]. Functional unit is defined as "1 kWh electricity generated at the power plant". The software used for the LCA model and analysis is Simapro 8.0.4.30 (PRé, 2014). A small portion of background LCI from ecoinvent version 3.1 (ecoinvent, 2014) were used because the background database in Simapro had been updated from version 3.1 to version 3.3 after the first draft of report and before incorporating the feedback received from nuclear power plants.

The system investigated covers the entire nuclear cycle, including uranium mining and milling, conversion, enrichment, fuel element production, nuclear power plant operation (operation during both electricity generation and outage period) and decommission, as well as waste processing and disposal. Reprocessing of fuel and the consumption of reprocessed fuel are not considered, due to the ban of reprocessing under Nuclear Energy Act in Switzerland since 2006.

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[3] LCI processes used in an LCA can be categorized into foreground processes and background processes. The foreground LCI processes represent the system under investigation, and for which the LCI data has to be collected. For example, in this study, the foreground processes are those which are directly part of the nuclear chain (uranium mining and milling, enrichment and fuel production, power plant operation and radioactive waste treatment), as illustrated in Figure 2.1. Correspondingly, there are also background LCI processes, represented by consumption of fuels, electricity, chemicals and transport services in Figure 2.1. Those processes are taken from a background database. The combination of foreground and background LCI make up the life cycle of the product system investigated.

The production chains of materials, energy and transportation services required for these processes are also accounted for. All the processes mentioned above create direct or indirect environmental burdens (Figure 2.1).

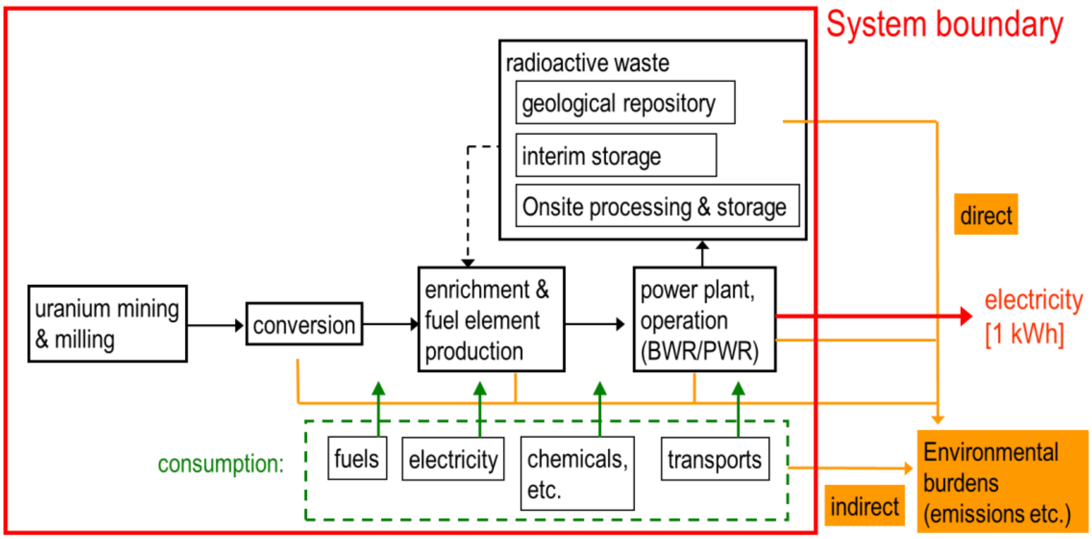

Figure 2.1: LCA scheme – system boundary and environmental burdens of nuclear power generation.

This work represents a continuation of the LCA activities concerning Swiss nuclear power in Dones, Bauer, and Doka (2009), ecoinvent (2014) and Bauer et al. (2012) (Figure 2.2). Updating and extending all relevant processes in the nuclear cycle in close collaboration with nuclear power plant operators has been in focus. Compared to previous LCA, the inventory data are much more detailed – especially for power plant operation and waste treatment – and represent the latest available information. The new life cycle inventory data compiled within this study build upon Bauer et al. (2012) and ecoinvent (2014) (v3.1) – comparison of "old" and "updated" LCI data always refers to ecoinvent v3.1 as "old"[4] and this study as "updated", respectively. In addition to updating previously existing inventory data, inventories for several new processes and components in the nuclear fuel cycle could be established, namely fabrication of control rods, decommissioning of the reactor, and waste treatment between the power plant and the interim storage.

4 Here it refers to the nuclear electricity production datasets in ecoinvent v3.1 that are used as background LCI in other LCA studies where nuclear electricity is consumed.

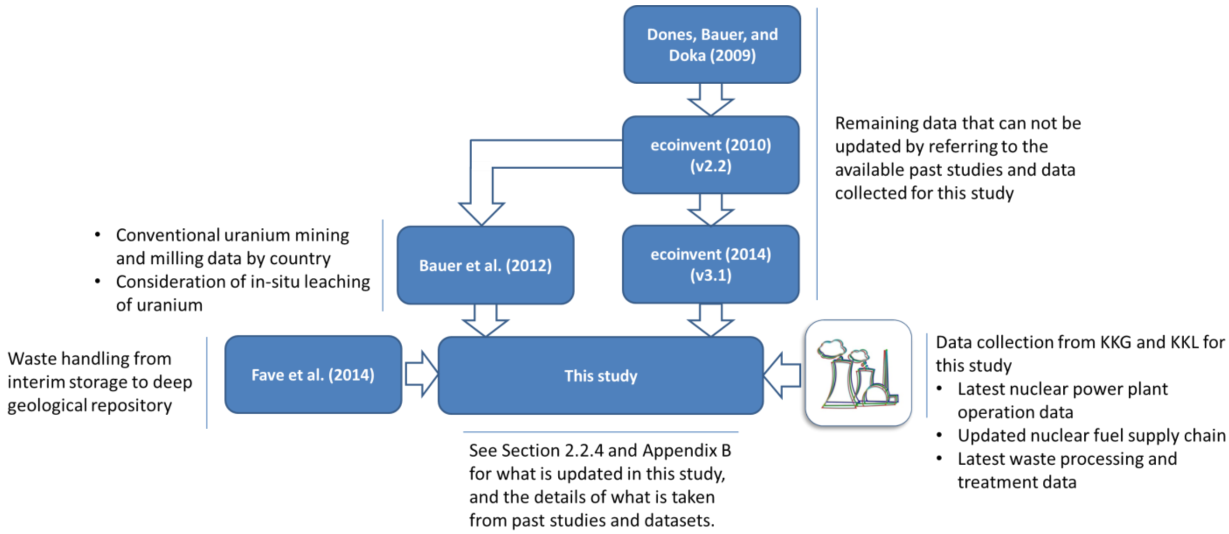

Figure 2.2: The relationship between this study and past studies and datasets.

Although there are in total five nuclear power reactors in Switzerland, only two of them are analyzed in this study: nuclear power plant Gösgen (KKG) and nuclear power plant Leibstadt (KKL), representing Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR), respectively. These two plants are selected, because in the total of 26.4 TWh of electricity production from nuclear plants in Switzerland in 2014, KKG and KKL have contributed the majority of about 66% (BFE, 2014; KKG, 2014; KKL, 2014b); in addition, these two plants will most likely operate much longer than the reactors in Mühleberg and Beznau.

As shown in the analysis and discussion of LCA results (section 3), the type of reactor (PWR or BWR) has only limited impact on the results; much more important for most of the environmental burdens is the fuel supply chain, which is independent of the reactor type. This should be kept in mind for extrapolation of results of this analysis to other NPP.

2.1.1. Temporal aspects

Based on discussion with the stakeholders and operators of the nuclear power plants, it has been decided that the time horizon for the baseline scenario is set to be year 2017 (specified as "current"). This is mainly due to two reasons: 1) the fuel supply chains of KKL and KKG are changed in 2017 and are supposed to stay more or less constant afterwards, and 2) the supply of uranium for fuel element production for KKL and KKG until 2017 still had relatively large contributions of uranium reprocessed from diverse sources in Russia; for those, only limited data is reported in one available source, an environmental report by SCC (Siberian Chemical Combine). Moreover, complete information concerning different types of uranium products from SCC is not available, which does not allow for allocation of specific burdens to uranium ultimately used in Swiss power plants and would in any case most likely not comprehensively represent the environmental burdens associated with this specific fuel supply pathway. Therefore, to reduce the uncertainty and potential data gaps, all the updates for the current

Swiss nuclear power LCI represent the Swiss nuclear power system in 2017 (and afterwards). The updated plant operation data as well as some upstream uranium and fuel processing data are obtained from recent years depending on data availability, and it is assumed that the operation of the plant did not change in the baseline scenario for 2017.

2.2. Life Cycle Inventory (LCI)

The quantified flows of inputs and outputs of a system process are called Life Cycle Inventory (LCI), usually consisting of exchanges in terms of resource, material, energy flows, land use and emissions to water, air and soil. Key parameters of processes in the nuclear chain such as fuel burnup rate, enrichment level, spent fuel generation, supplies of fuels produced from different facilities, lifetime of nuclear power plants, annual electricity generation, plant efficiency, etc. were incorporated into LCI and the effects of variation of these parameters was investigated in sensitivity analysis. In order to evaluate future prospective scenarios, the likely future development of these parameters was estimated and the effect on LCA results was quantified. The detailed updated LCI by process are listed in the appendix, side by side with the last version of inventory data of Swiss nuclear power generation in ecoinvent version 3.1 (ecoinvent, 2014). Assumptions required for compilation of LCI data and extrapolations from raw data are documented in spreadsheets for each process, were shared with the corresponding data providers for verification, and are also provided in the appendix. The following section will introduce the overview of fuel supply chains for each plant, the quality of data by process, reference year(s) from which the updated LCI is derived from, and the detailed updates within each process of the nuclear cycle.

2.2.1. Fuel Supply Chain

This section serves as a general overview of fuel supply chains modeled in this study. Detailed assumptions by process can be found in section 2.2.4. The upstream fuel supply for nuclear power generation in 2017 is illustrated below for PWR (Gösgen) and BWR (Leibstadt), respectively. Percentage contributions from each supply facility with their country of location are listed. The percentage of contribution refers to the percentage of uranium supply from previous step to next step, therefore it always adds up to 100% (based on product mass) in each process.

Table 2.1: Fuel Supply for PWR (represented by KKG) in 2017 (KKG, 2014-2017).

<table>
<tr><th colspan="2">Uranium Mining and Milling</th><th colspan="2">Uranium Conversion</th><th colspan="2">Uranium Enrichment</th><th colspan="2">Fuel Assembly Production</th><th>Nuclear Power Generation</th></tr>
<tr><td>Canada</td><td>45%</td><td>Cameco, Canada (Blind River followed by Port Hope)</td><td>45%</td><td>Urenco, Germany, Netherland, UK</td><td>45%</td><td rowspan="2">Fuel Assembly, Area Lingen, Germany</td><td rowspan="2">100%</td><td rowspan="4">Gösgen Nuclear Power Production</td></tr>
<tr><td>Australia</td><td>55%</td><td>Areva, France (Malvesi followed by Pierrelatte)</td><td>55%</td><td>Areva, Georges Besse II, France</td><td>55%</td></tr>
<tr><td colspan="6" rowspan="2"></td><th colspan="2">Control Rod Assembly Production</th></tr>
<tr><td>Control Rod Assembly, Areva, France</td><td>100%</td></tr>
</table>

The fuel assemblies and control rods supplied to PWR are manufactured by Areva[5], with fuel assemblies supplied from Areva in Lingen, Germany, and control rod assemblies supplied from Areva in France. In 2017, about 45% of the enriched uranium used in fuel assemblies at PWR is supplied by Urenco, and the remaining 55% is supplied by Areva[6]. The detailed supply from Urenco is from European origin, and since Urenco has operations in Germany, Netherlands and UK in Europe, the breakdown in these three countries were estimated based on the annual production capacity (section 2.2.4.3). It should be noted that in reality, when the enriched uranium is supplied by Urenco in 2017, it also means that the fuel elements from previous fuel suppliers will stay in the reactor till around 2020. These are, however, not considered for the baseline scenario in this study, but partially (to the extent possible, limited by data availability) in the sensitivity analysis. Areva formerly produced enriched uranium by gaseous diffusion technology in the Georges Besse plant, but the operation ceased in June 2012, after a 33 years of continuous production (Areva, 2012). Instead, enrichment via centrifuge now is the only technology that the enriched uranium production from Areva relies on. The advantage of uranium enrichment through centrifuge is that this process is much less energy intensive than enrichment by diffusion. Uranium supplied to Urenco for enrichment is from Cameco in Canada, which also obtains the uranium in yellowcake from uranium mining sites in Canada.

Table 2.2: Fuel Supply for BWR (represented by KKL) in 2017 (KKL, 2014c).

Uranium Mining and Milling		**Uranium Conversion**		**Uranium Enrichment**		**Fuel Assembly Production**		**Nuclear Power Generation**
Canada	50%	Cameco, Canada (Blind River followed by Port Hope)	25%	Urenco Germany, Netherland, UK	50%	Westinghouse Västeras, Sweden	39%	Leibstadt Nuclear Power Production
		Areva, France (Malvesi followed by Pierrelatte)	25%					
Russia	50%	Sevesk Russia	50%	Sevesk Russia	50%	Areva Lingen, Germany	61%	
						Control Rod Assembly Production		
						Westinghouse Västeras, Sweden	39%	
						Areva, France	61%	

The fuel elements used in KKL are supplied by Westinghouse in Västeras, Sweden, and Areva in Lingen, Germany. The breakdown of uranium fuel assembly supply between these two facilities is calculated based on the origin of existing fuel loaded in the reactor. Westinghouse receives the enriched uranium for fuel element production from Urenco, while Areva obtains it from Seversk, Russia. The particular supply breakdown of uranium conversion by country upstream of Urenco enrichment is unclear, so half of the supply is assumed to be from Urenco, and the other half is from Areva, France. Since the enrichment service in Urenco has operations in four countries, the electricity supply mix by country for enrichment is estimated based on annual country-specific production capacities of Urenco in 2014. The uranium in yellowcake that is supplied to the conversion and enrichment facilities in Seversk, Russia, is assumed to be from conventional uranium mining in Russia, without consideration of uranium reprocessed from

5 Since early 2018, it is renamed as Framatome, however since this study was conducted earlier, Areva is used throughout the report.

6 Since early 2018, it is renamed as Orano, however since this study was conducted earlier, Areva is used throughout the report.

diverse sources due to lack of data. In reality, an (unknown) fraction of this uranium originates from disarmed nuclear weapons – complete data for the associated processes are not available to the authors of this report. The uranium in yellowcake supplied for uranium conversion in Cameco and Areva are both assumed to be from uranium mining in Canada (KKL, 2014c).

2.2.2. Key parameters for BWR and PWR nuclear cycles in the baseline scenario (reference case)

The key parameters and technical information for the baseline analysis are listed in Table 2.3 for PWR and BWR, respectively.

Data	Unit	PWR (KKG)	BWR (KKL)
Plant thermal capacity	MW_{th}	3002	3600
Plant lifetime[7]	years	50	50
Annual net electricity generation	GWh/year	8022	9458
Fuel type	-	UO_2	UO_2
Fuel assembly	kg of UO_2/assembly	502	200
Enrichment grade	-	4.95%	4.50%
Efficiency	-	33.6%	33.3%
Discharge fuel burnup	MWd_{th}/kgU	62.4	53.9
Fuel Consumption per kWh of Net Electricity Generation	kg of U/kWh net electricity	1.98E-06	2.32E-06
Intermediate level radioactive waste generation	m^3/kWh net electricity	1.57E-9	3.67E-9
Low level radioactive waste generation	m^3/kWh net electricity	2.24E-9	4.89E-9
Spent fuel generation	kg/kWh net electricity	2.96E-6	3.36E-6

Table 2.3: Key parameters and values estimated and used in the LCA for PWR and BWR in Switzerland representing the reference case of the analysis.

2.2.3. Data Quality

The quality of data used in this study varies by process. It depends on the source of the data available and how well it matches with its intended use in terms of time and geographical representativeness: historical data from various years and periods of time, respectively, depending on data availability, are used to represent the baseline system in 2017 and for future prospective scenarios from 2020 on; data interpolated from nearby or similar regions is used to

[7] Lifetime of 50 years was chosen as the assumption in this study in order to be consistent with assumption used in the study for NAGRA (Fave, Puhrer, & Bauer, 2014) so that the LCA model for deep geological repositories for radioactive waste disposal can be incorporated to this study, despite the fact that the current planning lifetime of KKG is 60 years (KKG, 2015).

approximate the data of target facilities or regions, if no specific data are available. Table 2.4 qualitatively summarizes the data quality by process concerning several aspects including: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation (European Commission, 2010). The quality of data is categorized with three qualitative levels: good, acceptable and poor. Most process data are considered to be of good data quality and some acceptable. The completeness of data for uranium mining and milling is considered to be half poor and half acceptable. This is because in the supply of uranium in yellowcake to conversion facility in Russia, only data for natural underground/open-pit uranium mining in Russia could be used in this analysis, whereas in reality, it is a mixed supply of uranium from mining and reprocessing from diverse sources with unknown breakdown in between, for which data availability is limited. For all the processes assigned with data quality level "acceptable", it indicates there is some geographical or temporal approximation used in the assumptions for compilation of LCI data. For processes assigned with data quality level "good", it means the data is derived from a satisfying source in recent temporal period. More detailed description for data used in each process can be found in section 2.2.4.

Table 2.4: Data Quality Overview by Process.

Process	Data Source Reliability	Completeness	Temporal Representativeness	Geographical Representativeness	Technological Representativeness
Uranium Mining and Milling	Acceptable	Poor / Acceptable [1]	Acceptable	Acceptable	Good
Uranium Conversion	Good	Acceptable	Good	Good	Good
Uranium Enrichment	Acceptable	Acceptable	Good	Good	Good
Fuel Element and Control Rod Fabrication	Good	Acceptable	Good	Good	Good
Nuclear Power Generation	Good	Good	Good	Good	Good
Decommissioning	Good	Acceptable	Acceptable	Good	Good

Good

Acceptable

Poor

Note:

[1] The half red in the completeness is because: for KKL, in the supply of uranium (in yellowcake) to conversion facility in Russia, only data for natural underground/open-pit uranium mining in Russia is used, whereas in reality, there is supply of uranium from reprocessing of uranium from diverse sources, for which no data is available.

2.2.4. Process Description and LCI Updates by Process

The following section will introduce the processes in the nuclear cycle in detail, and summarize the main updates of LCI data by process. The detailed and updated LCI datasets by process are provided together with the previous publicly available version of Swiss nuclear datasets (as in ecoinvent version 3.1 (ecoinvent, 2014) in the Appendix.

2.2.4.1. Uranium Mining and Milling (U_3O_8 production)

Uranium is a natural element with an average concentration of 2.8 parts per million in the crust of earth. Uranium ore is extracted and minded from the ground, and it is then milled and processed to produce uranium in the form of yellowcake, which is the main material required for producing nuclear fuel. Uranium can be extracted by underground and open-pit mining, which are also referred to as conventional mining of uranium. Process data for conventional mining and milling by country used in this analysis are based on the LCI data compiled in previous work by Bauer et al. (2012). In this study, the energy demand required for conventional mining and milling and the amount of tailings produced were estimated based on ore grade of mining sites for each country, and the operation emissions were adjusted based on the breakdown of open-pit and underground uranium mining in each country. In addition, uranium mining via in-situ leaching was taken into account, based on data from a study by Doka (2011). The process of uranium mining by in-situ leaching is not differentiated between different countries, and a global dataset for this process was constructed since this is the only data available.

The country supply mix of enriched uranium in yellowcake for PWR was updated as shown in Table 2.5. Updates were made based on the information provided by KKG that in 2017, 45% of the fuel originates from Urenco, Canada, and another 55% from Areva, France. The uranium supply to Areva is Australia, while the uranium supply to Urenco is from Canada.

Table 2.5: Raw data: Origin of KKG's uranium reserve at Areva (KKG, 2014-2017).

Supply by Country	Amount (tons U)
Supply from Canada	29.7 (natural uranium)
Supply from Australia	68.7 (natural uranium)
	30.5 (enriched uranium product)

The country supply mix of uranium in yellowcake for KKL was updated as shown in Table 2.2. Updates are based on the information provided by KKL that in 2017, 50% of the fuel originates from Canada, and another 50% from Russia. Although it is known that some of the Russian supply is from reprocessing of uranium from diverse sources, the environmental report from SCC (комбинат, 2012-2013) does not contain sufficient information to compile specific LCI data for this source of uranium. Instead, only uranium mined from natural resources in Russia can be considered, which is derived from data for the Priargunsky mine. The data quality for uranium supply from Russian origin is therefore considered to be poor, and requires further refinement in the future when more data is available.

2.2.4.2. Uranium Conversion (U_3O_8 to UF_6)

Uranium conversion process data is partially updated for the conversion in France (Malvesi followed by Pierrelatte) based on the environmental data published by Areva (Areva, 2012; "Gaseous and Liquid Releases, Environmental Monitoring Data at COMURHEX Pierrelatte," 2012; KKG, 2014, 2014-2017). A wet conversion technology is applied in this plant, in which impurities are removed through solvent extraction. The first step is carried out at Comurehex II Malvési plant, where nitric acid is used to separate impurities from uranium in yellowcake. Then the purified substance is dried and mixed with nitrogen and hydrogen to produce uranium trioxide (UO_3). It is then heated with hydrogen fluoride (HF) in hydro-fluorination process to produce uranium tetrafluoride (UF_4), which later reacts with fluorine via fluorination process to produce uranium hexafluoride (UF_6). The uranium hexafluoride is pressurized, cooled, condensed in solid form and stored in cylinders (Todd, 2014). Figure 2.3 illustrates the entire uranium conversion process at Areva, France.

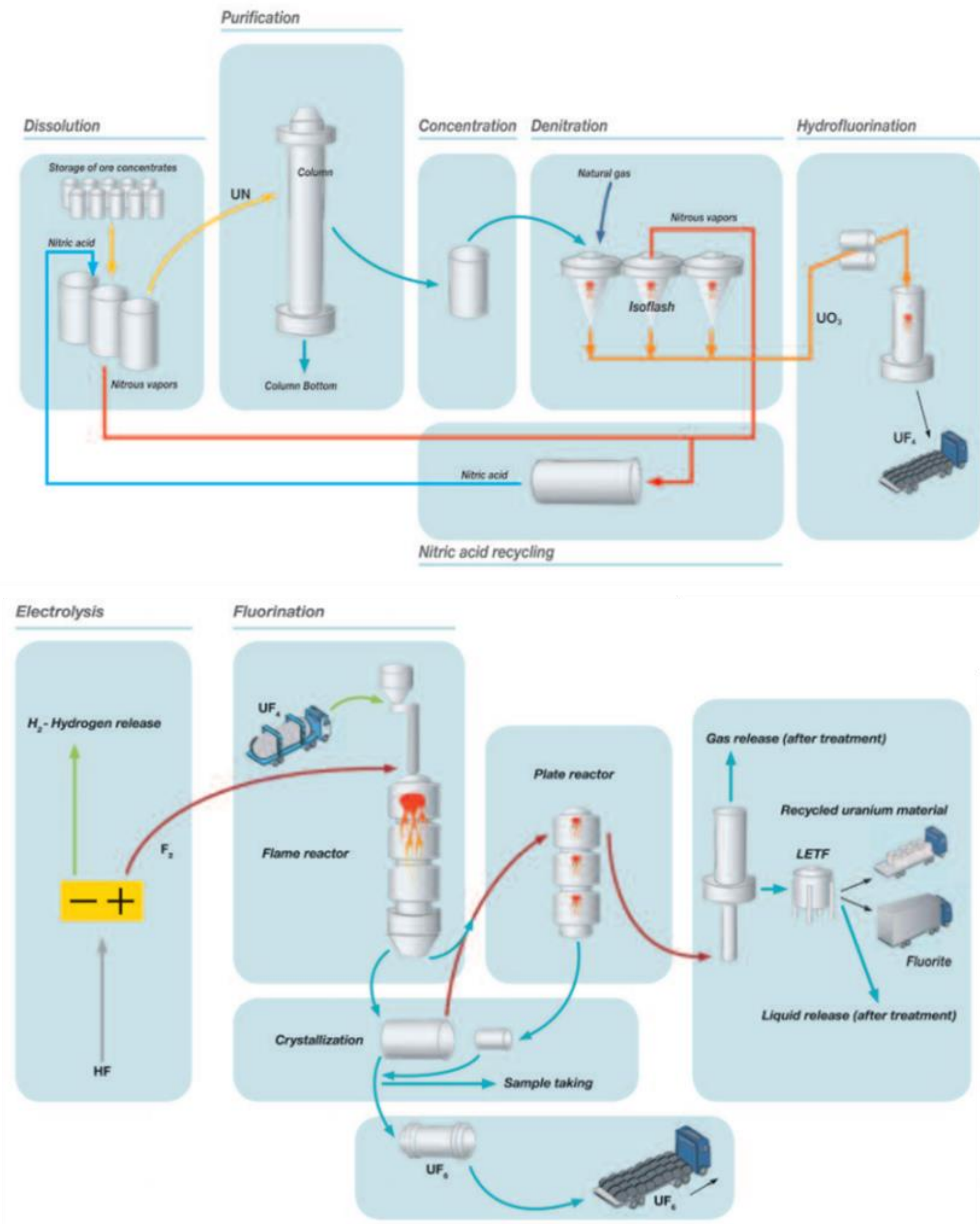

Figure 2.3: Two-step uranium conversion process at Areva, France (Areva, 2010).

New inventory data mainly concern the emissions to water, non-radioactive emissions to air, consumption of electricity, heating oil, propane, natural gas, as well as potable and industrial water consumption of the first conversion step, and emissions to water and air, as well as the inert, hazardous and low-level radioactive waste generation and processing of the second conversion step. Most of the inputs were derived based on the data reported in 2014, except that some emissions to water, low-level radioactive waste and hazardous waste were derived from 2012 due to data availability. The reported material flows and environmental releases are normalized by the production of 12,086 tons of UF_4 in 2014, 12,549 tons and 12,516 tons of UF_6 in 2014 and 2012, respectively. The uranium conversion service provided by Areva, France, for

BWR and PWR are differentiated by the supply of uranium in yellowcake as shown in Table 2.1 and Table 2.2, whereas the material, energy consumptions, emissions and waste generation are kept to be the same.

Uranium conversion process in Cameco, Canada (Blind River followed by Port Hope) is also partially updated based on the environmental report published by Cameco (*Annual Compliance Monitoring and Operational Performance Report Blind River Refinery*, 2014; *Annual Compliance Monitoring and Operational Performance Report Port Hope Conversion Facility*, 2014).

Wet process is also applied at the conversion plant at Cameco, Canada, but the intermediate products are slightly different from technology applied at Areva, France. The uranium concentrate is first delivered to a digestion tank, where nitric acid, water and other liquids are added to create slurry. The slurry is then pumped to the solvent extraction process. In the extraction column, solvent is added to the slurry to remove the uranium, and impurities are removed from the extract during a scrubbing stage. The extract is stripped to produce OK liquor (pure uranyl nitrate solution) and the solvent is regenerated. After that, the OK liquor is pumped to the boildown area where it is concentrated in a process that boils off water and nitric acid to produce uranyl nitrate hexahydrate (UNH). Then UNH, as a molten salt, is fed into the denitration pots. The UNH is heated to break it down into UO_3 and oxides of nitrogen. The granular UO_3 is then transferred to bins and weighted, and further transported to Port Hope site. The process at Port Hope side is started by electrolysis of hydrogen fluoride to produce hydrogen (H_2) and fluorine gas (F_2). By heating UO_3 and H_2 in a fluid bed reactor, UO_2 powder is produced. It is then mixed with hydrofluoric acid in the wet reactor to produce UF_4 slurry, which is then dried by the drum dryers and then a calciner to produce UF_4 powder. In the flame reactor, F_2 reacts with the dried UF_4 to form UF_6 gas. The gas is then converted to liquid UF_6 in the cold trap, stored in designed cylinders, solidified, and ready for transport to uranium enrichment plant.

The new inventory data for conversion at Cameco, Canada, mainly concern emissions to air, inert and hazardous waste generation and treatment and metals for recycling. The updates are derived based on published data from Cameco in 2014; LCI data are normalized by the annual production of 8750 tons of U in UF_6 in 2014 (World Nuclear Association, 2014).

Information on uranium conversion from Seversk, Russian is not available and was interpolated partially based on conversion process data from North America, and might be partially included in the process of enrichment in Russian supply. The detailed LCI for uranium conversion process in Russia derived based on North America data is included in the Appendix.

In both conversion processes at Areva and Cameco, each kg of uranium in yellowcake is able to produce 0.995 kg of uranium in uranium-hexafluoride considering 0.5% of loss, based on personal communication with KKG (2014-2017).

2.2.4.3. Uranium Enrichment (enriched UF_6, or Enriched Uranium Product (EUP))

Enrichment is the process in which the percentage of uranium-235 is increased by the process of isotope separation. There are mainly two technologies in the global market: enrichment by gaseous centrifuge or by gaseous diffusion. The major difference between these two technologies is that enrichment by diffusion is much more energy-intensive than centrifuge process, of about 40~50 times per separation work unit (SWU)[8] (World Nuclear Association, 2016). Enrichment facilities and their contributions of enriched uranium production for both KKG and KKL were updated as shown in Table 2.1 and Table 2.2. The previous version of Swiss nuclear power LCI is dominated by gaseous diffusion enrichment service provided by Areva, France, but in 2012 the plant upgraded the technology to centrifuge enrichment (Areva, 2012), which results in great reduction on process energy demand.

One supplier of the enrichment service in the Swiss nuclear cycle in 2017 is URENCO, which applies gaseous centrifuge enrichment technology (Figure 2.4). At enrichment plant, the UF_6 in solid form is first heated in an airtight and heated pressure vessel, so that UF_6 is vaporized and turned into a gas. The pressure of the gas is then reduced by control valves and restrictors before the gas is fed into the plant. The gaseous UF_6 enters the centrifuge. The heavier U_{238} is pushed by the centrifugal forces, and moved closer to the wall of the rotor than the lighter U_{235}. This results in the gas nearer the rotor axis with enriched U_{235}, and the gas closer to the wall becoming depleted in U_{235}. This process is repeated until the desired level of enrichment is reached. The enriched UF_6 with between 3% to 5% U_{235} isotope is then then compressed and packed into the special containers, which are then cooled and the UF_6 vapor inside solidifies on the walls of the container.

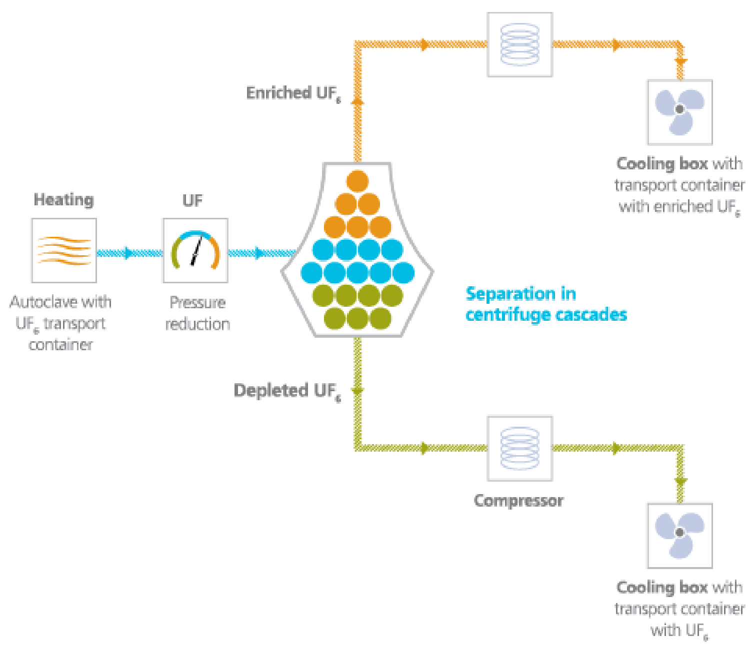

Figure 2.4: Enrichment process at Urenco (URENCO, 2016b).

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[8] Separation Work Unit (SWU, or kg SW, or kg UTA) is a common unit used in uranium enrichment, which represents the amount of separation work performed to enrich one kilogram of uranium to a certain level of enrichment (e.g. maximum of 5% for light water reactor fuels). It is a function of feedstock concentration, the enriched output, and the depleted tailings. The same amount of separation work may need different amount of energy depending on the efficiency of the separation technology.

The electricity supply for enrichment is updated based on Urenco's annual production capacity breakdown by country by the end of 2014, as listed in Table 2.6. All supplies are assumed to be medium voltage supply from the same mix. 40 kWh of electricity supplied by this mix of country supplies will be required per kg SWU (URENCO, 2016a). Updates are also made on the consumption of diesel, natural gas, heating oil, cooling water, decarbonized water, refrigerants, as well as the generation and processing of waste and wastewater based on the data published in Urenco (*Umwelterklärung URENCO Deutschland GmbH Urananreicherungsanlage Gronau*, 2013), Germany, and normalized by the annual production of 4100 tons of SWU in 2014.

Table 2.6: Enriched uranium production capacity breakdown by country, at URENCO, 2014 (URENCO, 2014).

Urenco, Country	Value (tons of SWU/year)	% of Electricity Supplied by Country
Urenco, UK	4900	34%
Urenco, Netherlands	5400	38%
Urenco, Germany	4100	28%

As for the enrichment at Areva, France, most of the previous data is used; the electricity demand is updated to be supplied by the medium-voltage grid supply from France, at 50 kWh per SWU (World Nuclear Association, 2015).

Part of the enriched uranium for KKL is supplied by Siberian Chemical Combine (SCC) in Seversk, Russia. Electricity and water consumption, wastewater generation, and emission to water and air data for enrichment from SCC was updated based on the SCC environmental report (*Открытое акционерное общество «Сибирский химический комбинат» ОТЧЕТ по экологической безопасности за 2013 год*, 2013) and annual report (2012) in 2012 and 2013 except for radioactive emission and process chemical consumption. The radioactive emissions are reported in percentage of maximum allowable limit (допустимая объемная активность, ДОА), and the maximum limit is concentration in Bq/m^3 of air based on Annex 1 (Приложение 1) in Standard of Radiation Safety -99/2009 (KKL, 2014b), whereas in LCA, total emissions in Bq is required in the inventories. As for process chemical consumption, the data is not available. SCC produces multiple products including energy from a CHP plant, nuclear products including uranium hexafluoride for enrichment, and enriched hexafluoride, and other metal products produced from uranium and plutonium. In this study, it is assumed that enriched uranium is the main product from the facility in Seversk, and environmental burdens estimated based on the data provided by SCC are all allocated to enriched uranium produced. The allocation of environmental burdens from enrichment should be refined in the future by allocating the burdens according to e.g. the revenue breakdown by product when data is available.

The enrichment levels of fuel are adjusted to 4.5% and 4.95%, for KKL and KKG respectively, and the required input of uranium, in uranium hexafluoride is assumed to be 1.34 kg/kg SWU when enrichment is at 4.95%, and 1.39 kg/kg SWU when enrichment is at 4.5%, calculated by using the formula (Bauer et al., 2012) below:

$$Y=2.5142*X^{-0.3952}$$

in which X represents enrichment level, and this formula is derived based on the given data in Swiss nuclear datasets in ecoinvent version 2.2, with lower enrichment level (ecoinvent, 2010).

Table 2.7: Enrichment and Amount of Uranium required in UF_6.

Parameter	ecoinvent v2		2016 updates	
Enrichment, in %	3.8	4.2	4.5	4.95
Required natural U in separation work unit, in kg natural U/kg SWU	1.48	1.43	1.39	1.34
Required SWU in fuel element, in kg SWU/kg U in fuel element	6.09	7.00	7.69	8.73
Required natural U in fuel element, in kg natural U/kg U in fuel element	9.0	10.5	10.7	11.7

2.2.4.4. Fuel Assembly and Control Rod Assembly Fabrication

The modelled LCI process of fuel assembly and control rod fabrication includes the conversion of UF_6 to UO_2. Although it is a separate step in reality, it is modelled as part of the fuel assembly and control rod fabrication as some of the data available is for all these processes, and cannot be split apart. The assumption of using chromium to approximate zirconium consumption due to unavailable data in the previous version of the Swiss nuclear power LCI data was updated. Now zirconium is used as the cladding material for the production of fuel rods. Fuel material composition was updated based on the following information for KKG (Table 2.8) and KKL (Table 2.9).

Table 2.8: The fuel assembly characteristics estimated at KKG (KKG, 2014-2017).

Data	Value	Unit
Weight of uranium dioxide per fuel assembly	502	kg/fuel assembly
Weight of structural material per fuel assembly	167	kg/fuel assembly
Weight of U per assembly	443	kg/assembly

Table 2.9: The fuel assembly characteristics estimated at KKL (KKL, 2014c).

Data	Value	Unit
Weight of uranium dioxide per fuel assembly	200	kg/fuel assembly
Weight of structural material per fuel assembly	100	kg/fuel assembly
Weight of U per assembly	181	kg/assembly

Energy required by fuel fabrication is updated to be supplied from the country of the corresponding facility locations, as shown in Table 2.1 and Table 2.2. Emissions of uranium alpha in Lingen, Areva, was updated based on the published data from "Deutschland Umweltradioaktivität und Strahlenbelastung Jahresbericht" in 2013 (Hachenberger, Trugenberger-Schnabel, Löbke-Reinl, & Peter, 2013). The amount of separation work unit needed per kg of enriched uranium in fuel assembly is calculated using the formula based on Dones et al. (2009), as shown below:

$$C = \frac{X_p - X_A}{X_E - X_A}$$

in which,
X_P is the enrichment grade;
X_A is the tailing grade;
X_E is the grade of U-235 in natural uranium

$$SWU = V(X_P) - V(X_A) + c\ [(V(X_A) - V(X_E)]$$

in which,

$$V(X) = (1 - 2X)\ln\frac{1 - X}{X}$$

The tailing grade is assumed to be 0.2%, and the U-235 grade in natural uranium is assumed to be 0.711%, according to personal communication with KKG (KKG, 2014-2017). The amounts of separation work needed per kg of enriched uranium in fuel assembly therefore are calculated as follows: 7.690 and 8.734 kg SWU are required per kg of enriched uranium in fuel assembly for KKL and KKG, respectively.

Some updated information on control rod and assembly production is estimated (Table 2.10) and incorporated into the updated LCI. This includes mainly the material required to produce the control rod assembly, including stainless steel, and absorber material consisting of silver, indium and cadmium.

Table 2.10: The control rod assembly characteristics estimated at KKG (KKG, 2014-2017).

Data	Value	Unit
Absorber Material Composition-Ag	80%	wt.%
Absorber Material Composition-In	15%	wt.%
Absorber Material Composition-Cd	5%	wt.%
Number of control rods per control rod assembly	20	p/control rod assembly
Number of control rod assemblies per year	2	p/year

There are some data gaps remaining in the fuel and control rod assembly fabrication, for example, it is known that hydrofluoric acid is produced during the conversion of UF_6 to UO_2, and being sold as a by-product. However, no environmental burdens are allocated to this by-product following a conservative approach.

2.2.4.5. Nuclear Power Generation (power plant operation)

In nuclear power production, updates were mainly made on the consumption of fuel and chemicals, emissions as well as waste generation and processing.

The consumption of fuel is calculated based on plant's latest -thermal-electric efficiency and burnup rate of fuel, using the formula below. The fuel burnup rate for KKG is 62.4 MWd/kg of uranium (KKG, 2014-2017), and 53.9 MWd/kg of uranium for KKL (KKL, 2014a). The electric-thermal efficiency for KKG is 33.6%, and 33.3% for KKL, corresponding to fuel consumption rates of 1.98E-6 and 2.32E-6 kg of uranium per kWh of net nuclear electricity production at KKG and KKL, respectively.

$$Fuel\ \ Consumption = (Fuel\ \ Burnup * 24\frac{hrs}{day} * 1000\frac{kWh}{MWh} * Electric\_thermal\ \ Efficiency)^{-1}$$

in which,
fuel consumption, in kg of uranium in fuel assembly/kWh of net electricity production;
fuel burnup, in MWd/kg of uranium;
electrical_thermal efficiency is the ratio of net electricity production and total thermal energy production

Chemical consumption was updated for KKG and KKL based on the latest information available for both KKG (Table 2.11) and KKL (Table 2.12). For KKL, since the chemical consumption data obtained is the average data from 2013 and 2014, the consumption per kWh of net electricity production is estimated by normalizing the total consumption below by average net electricity production in 2013 (9692 GWh/year) and 2014 (9458 GWh/year) at KKL. Similarly, for KKG, the chemical consumption data is obtained from 2014, and thus the consumption per kWh of net electricity production is estimated by normalizing by net electricity production in 2014 at KKG (8022 GWh/year).

Table 2.11: Chemical demand in primary water circuit and water steam cycle at KKL (KKL, 2014c).

Data	Value	Unit
Zinc oxide (depleted)	23	kg/ year
Hydrogen	150000	Nm^3/year
Platinum	620	g/cycle or year
Oxygen	75000	Nm^3/year
Condensate polishing plant powdered resin (dry)	2100	kg/year
Reactor water clean-up powdered resin (dry)	480	kg/year
Radioactive waste treatment powdered resin (dry)	180	kg/year
Radioactive waste treatment bead resin (dry)	94	kg/year
Fuel element pool powdered resin (dry)	570	kg/year
Suppression pool bead resin (dry)	120	kg/year
Demineralizer regeneration-sulfuric acid (96%)	15000	kg/year
Demineralizer regeneration-sodium hydroxide (30%)	15000	kg/year
Hydrogen for HWC plus generator	180000	Nm^3/year
Oxygen for HWC	83000	Nm^3/year
Carbon dioxide for flushing the generator	500	Nm^3/year
Argon for welding	5000	L/year
Oxygen for welding	3	Nm^3/year
Acetylene for welding	200	L/year
Liquid nitrogen for analyzing equipment	6500	L/year
Gaseous nitrogen for analyzing equipment	1500	L/year
Argon for analyzing equipment	5000	L/year
P10 (methane 10%/argon 90%)	6000	L/year
Burnt lime (CaO)	2500000	kg/year
$FeClSO_4$ (13.3% Fe aqueous solution)	880000	kg/year
Flocculation aid (Magnafloc 156, polyacrylamid)	4300	kg/year
Scaling inhibitor and dispergent (GENGARD GN8070Pol)	10000	kg/year
Sulfuric acid (H_2SO_4 96%)	370000	kg/year
Sodium hypochlorite (13%)	50000	kg/year
Hydrogen peroxide (35%)	75000	kg/year

Table 2.12: Chemical demand in primary water circuit and water steam cycle at KKG (KKG, 2014-2017).

Data	Value	Unit
Cation ion-exchange resin (Leiwatit S200)	800	kg/year
Anion ion-exchange resin (Leiwatit M800)	800	kg/year
Boric acid	116	kg/year
Lithium Hydroxide (Li_7OH-H_2O)	13	kg/year
Zinc	1.78	kg/year
Hydrazine (15%)	47.5	kg/year
Iron chlorosulfate (Eisenchlorsulfat)	1614	tons/year
Lime milk/lime powder 20% (Kalkmilch)	5775	tons/year
Calciumoxid 100% (Branntkalk)	1162	tons/year
Flocculant 100% (Flockungshilfsmittel)	5	tons/year
Polycarboxylic acid 100% (Härtestabilisierungsmittel)	32	tons/year
Hydrogen peroxide based biocide (Sanosil)	17638	liters/year
Javel water (Javelwasse)	31	tons/year
Lime sludge production (Kalkschlammproduktion)	10188	tons/year

The emissions to water and to air from power plant operation is updated both for KKG and KKL based on the published data from “Umweltradioaktivität und Strahlendosen in der Schweiz” (Cartier, Habegger, & Leupin, 2014), and the detailed raw data on emissions can be found in the Appendix. Since the emissions in 2014 were used, they are normalized by the net electricity production in 2014 at KKG (8022 GWh/year) and KKL (9458 GWh/year). Waste categorization, generation and processing were updated according the latest available data from nuclear power plants, as listed in Table 2.13 and Table 2.14. The handling of waste from nuclear power plants to interim storage in Zwilag is the main focus of this update, while the LCI for waste handling and storage from Zwilag to final storage in the geological repository was taken from the study PSI performed for NAGRA in 2014 (Fave et al., 2014).

Table 2.13: Waste generation at KKL (KKL, 2014c).

Data	Value	Unit
Low- and medium-level radioactive waste	40*	m3/year
Combustible and meltable waste (in the last 10 years)	27~53*	m3/year
Finally conditioned (in the last 10 years)	20~40*	m3/year
Combustible and meltable waste (before 1999)	20*	m3/year
Finally conditioned (before 1999)	60~120*	m3/year
Combustible and meltable waste (before 1999)	15000	kg/year
Finally conditioned (before 1999)	20000~40000	kg/year
Spent core components originating from KKL, 1993-2011	17500	kg
Control rods	133	pieces
Control rod weight	99	kg/piece
Control rod height	4.4	m
Total weight of control elements	13100	kg
FA channels	45	pieces
FA channels	1700	kg
Contaminated and activated neutron flux measuring lances (NFML)	46	pieces
Contaminated and activated neutron flux measuring lances (NFML)	1000	kg
Neutron sources (NS)	6	pieces
Neutron sources (NS)	40	kg
Water separator bolts (WSB)	32	pieces
Water separator bolts (WSB)	900	kg
Control elements after removing of pins and rollers packed into 200 l- drum	86	containers
Packaging density for control elements packed into 200 l- drum	1.25	g/cm^3
Control elements after removing of pins and rollers packed into MOSAIK	12	containers

*Note: all the volumes of waste include the volume of waste containers.

Waste generation at KKG in nuclear electricity production process was updated based on latest data collected from 1979-2014. Data for low and intermediate level radioactive waste was updated in KKG with more detailed waste categorization (eg. treatment of resin, concentrate, etc.) and waste treatment data (eg. with bitumen, concrete, electricity demand during drying and other processes, etc.).

Table 2.14: Waste generation at KKG (KKG, 2014-2017).

Data	Value	Unit
Number of pieces - low and intermediate level waste, generation per year, 200L-drums	68.7	drums/year
Concentrate in bitumen in drum per year (considered in low and intermediate level waste treatment above)	31.4	drums/year
Ion exchange resins in bitumen in drum per year (considered in low and intermediate level waste treatment above)	10.2	drums/year
Filter in cement per year in drum per year (considered in low and intermediate level waste treatment above)	1	drums/year
Activated metals in cement per year (considered in low and intermediate level waste treatment above)	0.4	drums/year
Residual from incineration per year (considered in low and intermediate level waste treatment above)	25.7	drums/year
Wastewater generation (Abwasserabgabe; considered under concentrate treatment in low and intermediate level waste treatment)	7514	m3/year
Weight of ion-exchange resin generation per year	700	kg/ year
Number of pieces - low and intermediate level waste, generation per year, MOSAIK casks	0.14	casks/ year
Number of pieces - low and intermediate level waste, 1 m3 canisters (no longer in production), generation per year	2.5	canisters/year
Number of pieces - low and intermediate level waste, generation per year, 4.5 m3 canisters	0.3	canisters/year
Weight - low and intermediate level waste, generation per year, 200L-drums	23.5	tons/year
Weight - low and intermediate level waste, generation per year, MOSAIK casks	1.36	tons/year
Weight - low and intermediate level waste, 1 m3 canisters (no longer in production), generation per year	8.05	tons/year
Weight - low and intermediate level waste, generation per year, 4.5 m3 canisters	0.92	tons/year
Low and intermediate level waste, conditioned volume per year	18.44	m3/year
Volume - low and intermediate level waste, generation per year, 200L-drums	14.6	m3/year
Volume - low and intermediate level waste, generation per year, MOSAIK casks	0.19	m3/year
Volume - low and intermediate level waste, 1 m3 canisters (no longer in production), generation per year	2.3	m3/year
Volume - low and intermediate level waste, generation per year, 4.5 m3 canisters	1.35	m3/year
Low level radioactive waste for incineration, volume	17.6	m3/year
Low level radioactive waste for incineration, number of drums	13.5	tons/year
Low level radioactive waste for incineration, weight	80.9	drums/year
Waste from incineration to low and intermediate level radioactive waste treatment	6.4	m3/year
Residue after incineration vitrified per year (considered in low and intermediate level waste treatment above)	25.7	drums/year

Updated information for waste containers including drums, casks, canisters and concrete containers together with the transport needed between the NPP and interim storage and container manufacturing location was added. The property of different waste containers that were considered in their production can be found in Appendix. There is also an overview of waste packaging, specifying which type of waste is packed into which containers in Appendix. In addition, more detailed data were obtained from KKG, in particular on the treatment of low and intermediate radioactive waste (such as ion-exchange resins, liquid concentrate, filters and activated metals), hazardous waste generation (including diverse waste oils, sludge, abrasive waste (corundum), and diverse aqueous waste), and other waste generation (including calcium carbonate precipitation from water treatment, used electrical and electronic equipment, used cables, and waste wood), as listed in Table 2.15.

Table 2.15: Hazardous and other waste generation at KKG (KKG, 2014-2017).

Data	Value	Unit
Hazardous Waste Generation (hazardous waste, non-radioactive) >10 t/year		
diverse waste oils	33.3	t/year
Sludge	76.8	t/year
abrasive waste (esp. corundum)	46.4	t/year
diverse aqueous waste	8.5	t/year
Other waste Generation (non-hazardous waste) > 10 t/year		
calcium carbonate precipitation from water treatment	10900	t/year
electrical and electronic equipment	4.8	t/year
cables	27.7	t/year
wood	49	t/year

Electricity demand from grid during annual outage period were added for both KKG and KKL, assuming medium-voltage Swiss grid supply, of 40’000 MWh and 19’885 MWh per year, respectively. Lifetime of nuclear power plants was assumed to be 50 years as in the BFE study by Bauer et al. (2012) and to be consistent with the study for deep geological repository PSI performed for NAGRA in 2014 (Fave et al., 2014), although there is information showing that both KKG and KKL may have extended lifetime of 60 years. However, this potentially underestimated lifetime is supposed to compensate the upgrade and maintenance of plants in recent years in terms of material and energy consumption, which could not be considered in this study. Reprocessing of fuel was excluded from the system as it was indicated during the data collection that reprocessing is very unlikely to be in the fuel cycle in the future.

2.2.4.6. Decommissioning

The data from the study “Stellungnahme für die technische Überprüfung der Kostenstudie zur Stilllegung der Kernanlage Leibstadt in der Schweiz (Stand 2011)” by TÜV (2012b) and data provided by KKG (KKG, 2014-2017) were mainly used to construct the LCI for decommissioning of the nuclear power plants. Decommissioning of the plant includes two major components: waste generation and treatment, as well as the energy consumption during decommissioning. Similar as the waste generation and processing at nuclear power plants, the focus of this update on decommissioning is on the waste generation and processing from the nuclear power plant to the interim storage in Zwilag. LCI data for waste handling from interim storage to deep geological repository is incorporated based on data in Fave et al. (2014). The waste generation and energy consumption are accounted for the entire plant for KKL and KKG, respectively. Similarly as plant construction, it is allocated to each net kWh of nuclear power generated from the plant during the lifetime, based on net electricity generation in 2014, which gives 2.5E-12 p/kWh for KKG, and 2.1E-12 p/kWh for KKL (the unit of "p" stands for "piece"; it represents all the materials and energy inputs, waste disposal, etc. required in nuclear plant decommissioning, and it is allocated to each kWh of electricity generated). The nuclear spent fuel assemblies generated during operation (nuclear power generation) also need to be moved to the geological repository at the end of the lifetime of the plants. These are accounted for within the contribution of "Waste" in the results in section 3.

Table 2.16: Data for Decommissioning of KKG (KKG, 2014-2017).

Data	Value	Unit
Timeframe and energy Consumption of Decommissioning		
Time frame after final shutdown until spent fuel removed from reactor building into external wet storage building	5	years
Decommissioning of power plant	9	years
Additional operation of external wet storage building	4	years
Decommissioning of external wet storage building	1.5	years
Electricity consumption in power during decommission	0.70	MW
Energy consumption in decommission oil and diesel	1.7E+05	liters/year
Water consumption in decommission	5.0E+06	liters/year
Waste generation from decommissioning		
Metals for recycling	606	tons
Inactive waste	242	tons
Materials for reuse (partly after decontamination)	172372	tons
Total Radioactive waste (with two options of categorization)	2992	tons
Radioactive waste categorization 1: primary radioactive materials for geological repository	2402	tons
Radioactive waste categorization 1: secondary radioactive materials for geological repository	590	tons
Radioactive waste categorization 2: middle active (casks with shielding)	59	tons
Radioactive waste categorization 2: low active waste	2'933	tons
Transport in decommissioning		
transports of low level waste (drums) to interim storage by truck during operation	3	per year
transports of low level waste (drums) to interim storage by truck after operation	145	trips
transports of MOSAIK casks to interim storage by truck after operation (intermediate level waste)	244	trips
transports of concrete containers to interim storage by truck after operation (low level waste)	521	trips

Table 2.17: Data for Decommissioning of KKL (KKL, 2014c)

Data	Value	Unit
Electricity consumption during decommissioning		
Total Radioactive waste packed into 200-l drum	1.20E+08	kWh/KKG
Net electrical power at KKG	1010	MWe
Net electrical power at KKL	1275	MWe
Waste generation and handling from decommissioning		
Total Radioactive waste packed into 200-l drum	3470	pieces
Total Radioactive waste packed into 200-l drum	1178	tons
Total Radioactive waste packed into LC1	70	pieces
Total Radioactive waste packed into LC1	1112	tons
Total Radioactive waste packed into LC2	327	pieces
Total Radioactive waste packed into LC2	4081	tons
Total Radioactive waste packed into LC2 with 80 mm lead	2	pieces
Total Radioactive waste packed into LC2 with 80 mm lead	21	tons
Total Radioactive waste packed into MOSAIC container type II with 20 mm lead	17	pieces
Total Radioactive waste packed into MOSAIC container type II with 20 mm lead	6	tons
Total Radioactive waste packed into MOSAIC container type II with 40 mm lead	20	pieces
Total Radioactive waste packed into MOSAIC container type II with 40 mm lead	6	tons
Total Radioactive waste packed into MOSAIC container type II with 60 mm lead	118	pieces
Total Radioactive waste packed into MOSAIC container type II with 60 mm lead	54	tons
Total Radioactive waste packed into MOSAIC container type II with 80 mm lead	54	pieces
Total Radioactive waste packed into MOSAIC container type II with 80 mm lead	21	tons
Metals for recycling	715	tons
Inactive waste	1085	tons
Materials for reuse (partly after decontamination)	284025	tons
Total radioactive waste	6479	tons
Primary radioactive waste	5346	tons
Secondary radioactive waste	1133	tons

The material demand for manufacturing special waste containers (e.g. different concrete containers used in deep geological repository) are refined according to the NAGRA study on waste packing in geological repository in 2014 (Stein, 2014). Note that for KKL, although the raw data indicates that several types of MOSAIK casks with different lead shielding are used to pack the waste, there is only one general type of MOSAIK cask assumed to be used in this study, and therefore the difference in lead material demand for different MOSAIK casks was neglected.

The energy demand for waste container production is based on data from Fave et al. (2014), which provides a general estimate of electricity demand for processing of different metals. Waste generation, transportation, processing and energy demand required for decommissioning of the plant was updated based on the cost study for KKG and KKL in 2011 (TÜV, 2012a, 2012b).

2.3. Sensitivity analysis

There is uncertainty in LCI data and the associated LCA results, and it is essential to understand how sensitive these results are regarding these uncertainties. In this study, sensitivity analyses are carried out concerning factors which are highly uncertain, or which have potentially substantial influence on the results (based on the results presented in section 3.1.1). They can be categorized into three types of sensitivity analysis: 1) the sensitivity of reference data year, which compares the impact of data reference years used in deriving LCI, specifically comparing using data from 2014 only, versus using data from long-term historical records; 2) the sensitivity of modeling choices, which investigates the impact of different options of modeling the Swiss nuclear chain; 3) the sensitivity of value ranges for key raw data, which considers the potential ranges of important raw data that are used to derive LCI, and the resulting ranges on LCA results.

The analysis is limited to the impact categories with recommendation level I and II by ILCD (see Table 2.21). Two scenarios are included for the sensitivity of reference data year (long-term and short-term), while three scenarios (best-case, worst-case and baseline) are constructed for the sensitivity of modeling choices and key raw data ranges, using assumptions representing "best and worst cases". The ranges of results provided by the sensitivity analysis are supposed to represent the potential variability of LCA results of nuclear power in Switzerland considering different types of uncertainties.

When the difference between scenarios are substantial, contribution analysis by nuclear processes is performed to understand how the differences are caused in connection with the assumptions, and the related results in section 3.1. The contribution of process i in a certain impact would be calculated using the formula below:

$$C_i = \frac{E_{ia} - E_{ib}}{E_a - E_b}$$

where:
C_i is the contribution of process i;
E_{ia} is the impact of process i in scenario a;
E_{ib} is the impact of process i in scenario b;
E_a is the impact of scenario a;
E_b is the impact of scenario b;

In each impact category, the sum of contributions from all processes adds up to be 100%:

$$\sum C_i = 100\%$$

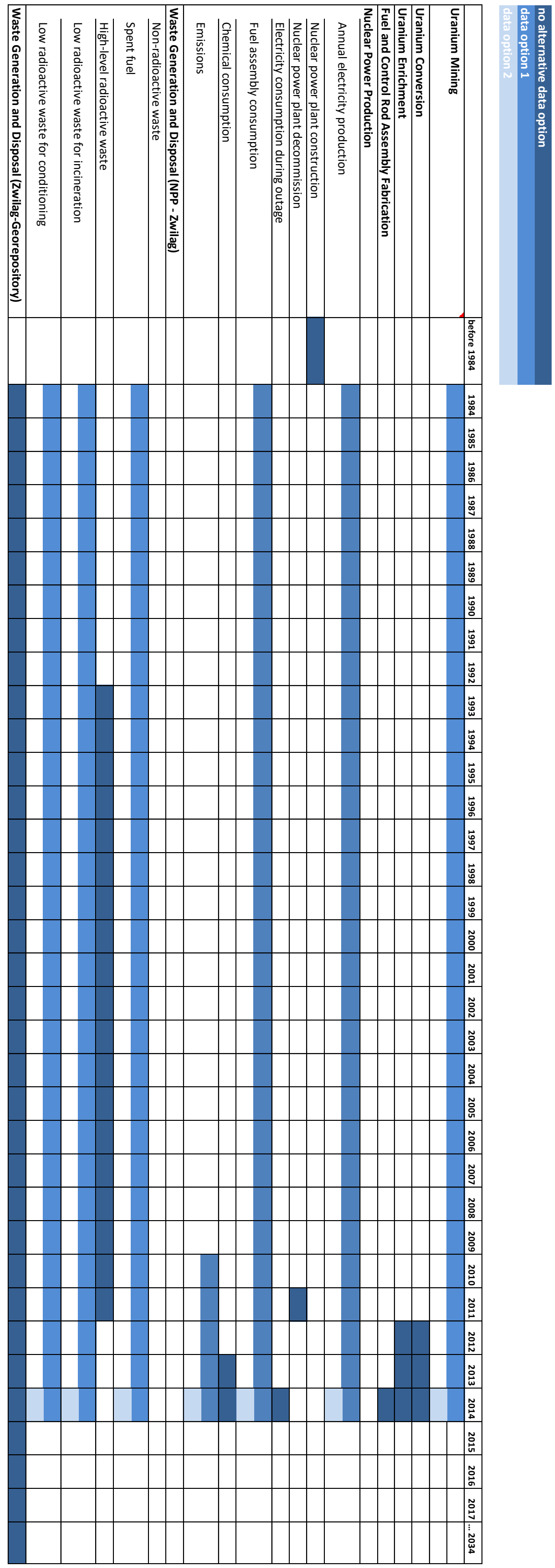
2.3.1. Sensitivity of reference year of LCI data

LCI data (e.g., for power plant operation) can be derived differently based on the data available: either from data in the most recent year (i.e. 2014), or data based on the average condition in longer historical records. LCI input derived from the former is supposed to illustrate the environmental impact at the point of baseline scenario, while the latter (in case of complete data availability) would reflect the average environmental burdens from the first year of operation till the time of baseline scenario.[9] In this study, LCI using both approaches are compared in section 3.4 for BWR. The sensitivity of reference data year is only performed for BWR, since the same kind of sensitivity analysis for PWR would not provide any meaningful additional insights.

Two options of reference years used in deriving LCI data were analyzed for BWR, and the detailed reference years by process are shown in Table 2.18 below, with the options of using historical record data (option 1) and data in 2014 only (option 2) for some processes, and “no alternative data option” in other processes. When certain processes are assigned with “no alternative data option”, it means that the data used in this process is the only data available, and cannot be divided by year, thus it is impossible to derive two sets of LCI, based on long-term historical record and data from 2014 only, respectively. Most of the data listed under each process are inventory data, with one exception: “annual electricity production” under “nuclear power production”. Instead, it is the denominator to calculate the inventory data of nuclear chain processes, so that they correspond to one functional unit. Since the year by year supply of uranium in yellowcake based on historical data is unclear, the current global average supply is used in the process of uranium mining and milling in the long-term option.

[9] In this context, it needs to be considered that background LCI data always represent a certain reference year in the (recent) past and sensitivity analysis of this kind can only be performed for foreground LCI data. Therefore, the validity of “average over lifetime” LCA results will always be limited.

Table 2.18: Data reference year by process (BWR); option 1 – long-term, option 2 – short term.



2.3.2. Sensitivity of modeling choices

There are different choices to model the same product system in LCA. The sensitivity of modeling choices is meant to investigate what processes are used to form the system, how they are connected, and how these different structures representing the same system would affect the LCA results. Uranium mining and milling, as well as uranium enrichment are selected processes to investigate different modeling choices, based on their overall contributions on environmental impacts as shown in section 3.1, and based on the inherent uncertainties in these parts of the nuclear power chains. The following choices are explored by process:

Uranium mining and milling:

In the baseline scenario, a mix of uranium in yellowcake supplied from different countries is assumed, based on the data provided by the nuclear operators. Because the contribution of uranium mining and milling in life cycle environmental impacts is substantial (Figure 3.1 & Figure 3.2), supplies with "best" and "worst" overall environmental performance in uranium mining and milling are explored in this sensitivity analysis, as opposed to the assumptions made in the nuclear chain of baseline scenarios (shown in Table 2.1 and Table 2.2).[10] According to the results of uranium mining and milling shown in Figure 3.12, considering all the impact categories, the overall "best-performing" process is global uranium mining through in-situ leaching, and the "worst" is uranium mining and milling carried out in Australia (mostly due to the lower ore grade for uranium mining and milling in Australia, thus more tailing is generated and needs to be treated; this assumption is subject to high uncertainty because of the methodology applied to estimate the amount of tailing generation and treatment as according to Bauer et al. (2012) and in general high uncertainty of inventory data for uranium mining and milling (as shown in Table 2.4); see section 3.2 for more details) for PWR, and in Russia for BWR. Note that the criteria for overall environmental impacts is based on the number of best-performing and worst-performing environmental impact categories, which means that, uranium mining and milling in Australia and Russia has the highest number of impacts with worst environmental performance compared with other countries, whereas global uranium mining via in-situ leaching has the least number of impacts with the best environmental performance. The implication of this criterion to define the best- and worst-performing uranium mining a milling process is that certain impacts of the worst-performing option might not necessarily worse than the corresponding impact in baseline scenario or best-performing option.

Uranium enrichment:

Based on the definition of nuclear chains in the baseline scenario (section 2.2.1), it is assumed that part of the enriched uranium supplied to the Swiss nuclear power production is produced by URENCO. It is also known that URENCO enrichment service currently has facilities in three

[10] This sensitivity analysis does not include the potential fuel supply with uranium reprocessed from diverse sources in Russia due to lack of appropriate information for compilation of inventory data.

different countries in Europe (Table 2.6). Although the switch from enrichment by diffusion to enrichment by centrifuge in the current Swiss nuclear chain has greatly reduced the energy demand of enrichment process, it is still a comparatively energy-intensive process. In the baseline scenario, it is assumed that the electricity supply for enrichment that is carried out by URENCO is a mix of supplies, based on the annual, facility specific production of enriched uranium in 2014. Comparing the environmental performance of electricity production in these three different countries (Appendix section 5.2), it shows that the overall environmental performance of electricity production in the Netherlands is the best among four countries, and thus is selected as the best-performing electricity supply for uranium enrichment in this sensitivity analysis (i.e. representing 100% of the URENCO supply by the facility in Germany). The supplies from UK and Germany are about the same. Due to geographical proximity of Germany to Switzerland, the electricity supply from Germany is assumed be to the worst-performing electricity supply in uranium enrichment (i.e. representing 100% of the URENCO supply by the facility in the Germany).

2.3.3. Sensitivity of key raw data range

The sensitivity analysis of key raw data range concerns the variation of key parameters and data used within the complete nuclear fuel cycle. The sensitivity of parameters and assumptions in the LCI data is investigated for KKL and KKG in order to provide ranges of potential impacts of nuclear power in Switzerland. Variation of parameters and assumptions include:

Enrichment of uranium:

- Energy demand in enrichment: 40 to 50 kWh/kg SWU
- Level of enrichment: between current enrichment levels of fuels in Swiss nuclear power plants to 5%, as 5% is the current enrichment upper-limit for the light water reactors.

Discharge burnup rate of fuel: corresponding to the increase in level of enrichment; assumed to reach the limit of light water reactor burnup rate of 65 MWh/kg U would be reached at 4.95% of enrichment.

Lifetime of nuclear power plants: 50 to 60 years, as the further extension of lifetime of 10 years is already placed for KKG and KKL. This is however without the considering of the infrastructure upgrade after the completion of nuclear power plant construction due to lacking of data. The assumption of 50 years lifetime for nuclear power plant is also kept for waste disposal and transport in deep geological repository due to model compatibility reason.

Uranium waste processing: due to the high energy demand of plasma incineration of radioactive waste, and its potential fluctuation between the volume expected and actually generated, it is selected to vary in a range of ±20%.

Table 2.19: Sensitivity performed for key performance data in the nuclear chain.

Parameters		BWR		PWR	
		Best-performed	Worst-performed	Best-performed	Worst-performed
Uranium enrichment	**Electricity demand (kWh/kg SWU)**	40	50	40	50
	Level of enrichment (%)	5%	4.5%	5%	4.95%
Discharge fuel burnup (MWd_{th}/kg U)		65	53.9	65	62.4
Nuclear power plant lifetime (years)		60	50	60	50
Radioactive waste for plasma incineration (m^3/kWh of net electricity production)		3.91E-09	5.87E-09	1.79E-09	2.69E-09

2.4. Prospective Scenarios

The prospective scenarios of Swiss nuclear power generation were constructed by using projected discharge fuel burnup rate, net electrical-thermal efficiency of nuclear power plants, and annual electricity production at the time horizon of 2020, based on the discussion with nuclear plant operators from KKG and KKL. Year 2020 is selected as prospective time horizon, as according to the nuclear power plant operators, any estimates after 2020 would be associated with too high uncertainties from their perspective. The main parameters that are set to be different from baseline scenarios are: fuel discharge burnup rate, annual electricity production and the electric-thermal efficiency of the plants. These estimates were provided by the personal communication with KKG and KKL, respectively.

Table 2.20: Fuel discharge burnup, annual electricity production and plant efficiency for PWR and BWR in baseline and prospective scenarios.

Parameters	PWR Prospective	BWR Prospective	PWR Baseline	BWR Baseline
Fuel Discharge Burnup (MWd/kg U)	65.0	55.2	62.4	53.9
Annual Net Electricity Production (GWh/year)	8072	9914	8154	9458
Plant Efficiency (%)	33.6%	33.3%	33.6%	33.3%

2.5. Life Cycle Impact Assessment (LCIA) Method

In order to perform life cycle impact assessment, an LCIA methodology needs to be selected. Several life cycle impact assessment methodologies have been developed in the past decades and the development is ongoing. The Institute for Environment and Sustainability in the Center of European Union Joint Research performed a review study on a range of LCIA models and characterization factors in 2011, namely "European Commission Joint Research Centre, Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook, Recommendations for Life Cycle Impact Assessment in the European context", with coverage of 11 impact categories. The review eventually recommended the methodology and characterization factors to be used in Europe, and assigned recommendation level to each methodology they selected (Hausschild et al., 2011).

In this study, eight "ILCD 2011 Midpoint" impact categories were selected, based on the general criteria that they have acceptable recommendation level and are relevant to the potential environmental impact of nuclear power generation. Table 2.21 has a detailed list of impact categories included in this study, together with their recommendation level, and particular reason to be included. Under recommendation level, level "I" represents "recommended and satisfactory", level "II" represents "recommended but in need of some improvements", level "III" represents "recommended, but to be applied with caution". There are impact categories assigned with "interim", which means that a method was considered the best among the analyzed methods for the impact category, but still immature to be recommended. These impact categories were filtered out of this study in the first place.

Table 2.21: ILCD midpoint impact categories with ILCD recommendation level and reason to be included in this study (Hausschild et al., 2011).

Impact Category	Methodology	Unit	Recommendation level by ILCD	Reason for being included
Climate Change	IPCC 2007 (100-year time horizon)(IPCC, 2007)	kg CO2 eq	I	Impact category that is relevant to climate change/global warming, and to be used to compare with other energy technologies on their global warming potential.
Particulate Matter	RiskPoll model (Rabl, 2004) and (Greco, Wilson, Spengler, & Levy, 2007)	kg PM2.5 eq	I	Primary and secondary aerosols represent an important impact on human health; main contributors: PM_{10}, NO_x, SO_2, and ammonia emissions to air.
Ionizing Radiation on Human Health	Human health effect model as developed by Dreicer, Tort, and Manen (1995) (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000)	kBq U235 eq	II	Highly related to nuclear power production and fuel cycle
Acidification	Accumulated Exceedance (Posch et al., 2008; Seppälä, Posch, Johansson, & Hettelingh, 2006)	molc H+ eq	II	Acidification represents an important impact on ecosystem quality; main contributors: SO_2, NO_x and NH_3 emissions to air.
Human Toxicity, Cancer & Non-cancer Effect	USEtox model (Rosenbaum et al., 2008)	CTUh	II/III	Human toxicity covers releases of toxic substances (e.g. heavy metals, hydrocarbons) to the environment and is often associated with mining activities.
Freshwater Ecotoxicity	USEtox model (Rosenbaum et al., 2008)	CTUe	II/III	Chemical usage and emissions to water may cause water toxicity.
Landuse	Model based on Soil Organic Matter (SOM) (Milà i Canals et al., 2009)	kg C deficit	III	Potential land disruption from entire uranium fuel cycle (mining, enrichment, etc.)

3. Life cycle impact assessment (LCIA) results

This section summarizes the LCIA results by environmental impact category. Analysis was performed to understand the contribution of the main processes in the entire nuclear cycle. It is followed by selected environmental impacts caused by electricity generation at PWR and BWR and the environmental performance of electricity from these two plants with other electricity generation technologies in Switzerland. A broader perspective (i.e. the comparison with other generation technologies) needs to be kept in mind when interpreting the LCA results of PWR and BWR: at a first glance, differences between those two plants in terms of LCA results might seem large for some indicators, but usually, these differences become almost negligible in comparison with other generation technologies. The selected environmental impacts are merely presented for PWR and BWR, and the results are not necessarily to be compared, as they are two different nuclear power generation technologies with different fuel supply chains.

Because uranium mining shows to be important in many impact categories, a more in-depth investigation was carried out on it, and the main causes of its relative high contributions are discussed by impact category. Several sensitivity analyses are performed, including the sensitivity of reference data year, the sensitivity of modeling choices, and the sensitivity of key raw data ranges. In the end, LCIA results of potential future scenarios are presented.

3.1. Baseline Scenario: LCIA Results

Figure 3.1 and Figure 3.2 show the relative contribution of each nuclear cycle process to the environmental impacts of the baseline scenario for electricity production from PWR and BWR, respectively. Impact by process is normalized by the total impact in each category so that the total impact per category adds up to 100%. In both PWR and BWR chains, uranium mining and milling is a major contributor to all impact categories, except the impact of ionizing radiation on human health, where the operation of the nuclear power plant (nuclear power production) for BWR also shows a similar contribution. Since the emissions of carbon-14 to air in BWR per kWh of net electricity production are much higher (about 5 times) than those of the PWR, and in addition there are emissions of cobalt-60, cesium-134 and -137 to water, which are not reported for PWR in the published numbers from “Umweltradioaktivität und Strahlendosen in der Schweiz in 2014” (Cartier et al., 2014), thus the direct burdens of BWR are higher than those of the PWR. Since the ionizing radiation characterization factors of these emissions[11] are higher than those of other radioactive emissions (well below 1 kBq U^{235} eq/kBq), the resulting contribution from the BWR plant to ionizing radiation is much higher than for PWR. Apart from uranium mining & milling and power plant operation, the other main contributors are waste processing and nuclear plant construction, but they are in general much less influential than the impact created by uranium mining and milling.

[11] carbon-14 to air: 10 kBq U^{235} eq/kBq; cesium-137 to water: 7.86 kBq U^{235} eq/kBq; cesium-134 to water: 6.79 kBq U^{235} eq/kBq; cobalt-60 to water: 2.07 kBq U^{235} eq/kBq

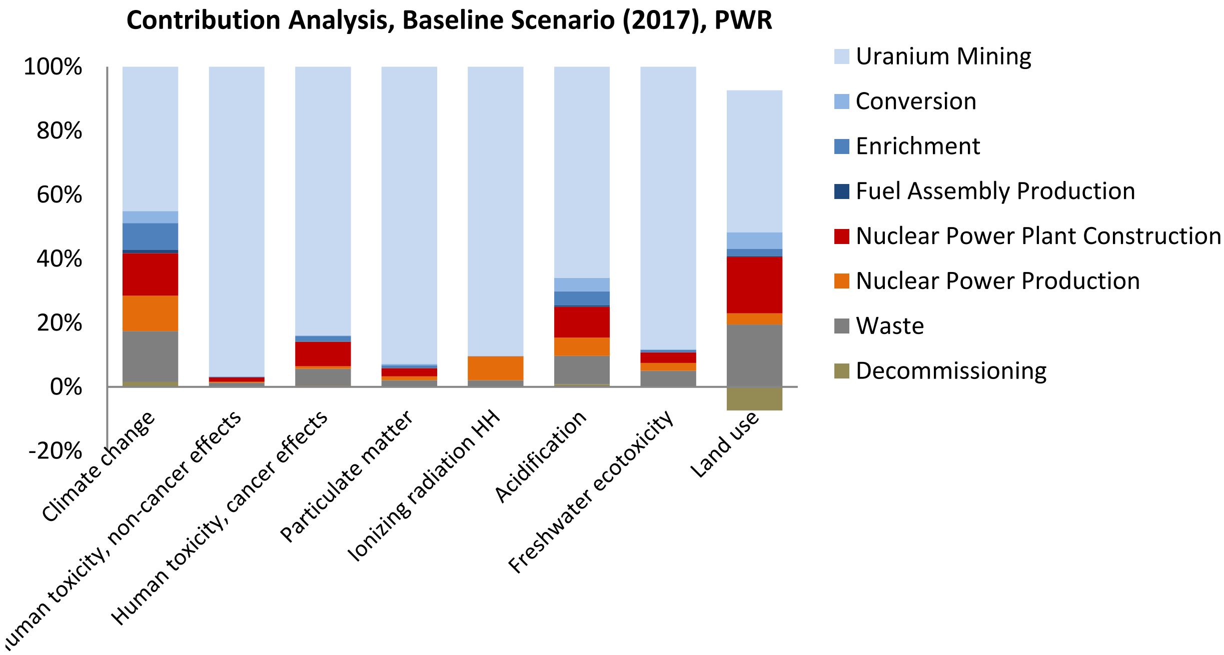


Figure 3.1: Contribution Analysis of Baseline Scenario (2017), PWR.

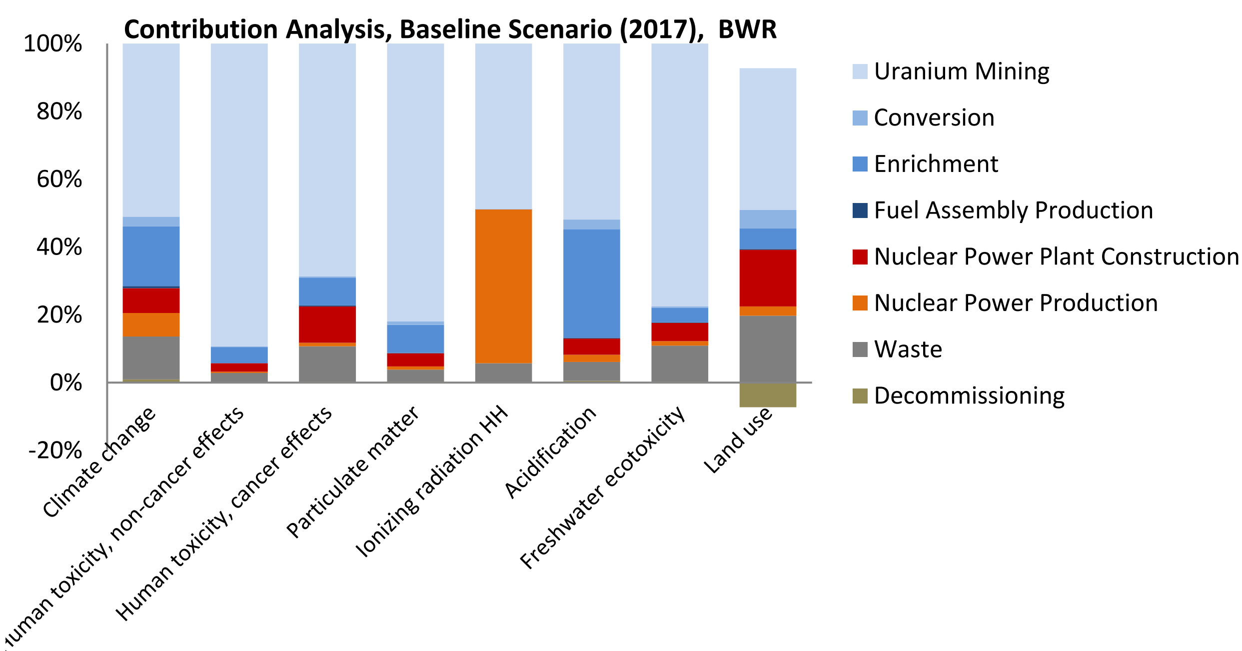


Figure 3.2: Contribution Analysis of Baseline Scenario (2017), BWR.

Processes including uranium mining and milling, conversion, enrichment, and fuel assembly production (processes colored in different shades of blue) represent the front-end processes of the nuclear power production. In the impact of climate change, the front-end contribution within the BWR chain (72%) is a higher than for the PWR chain (58%), mostly because the enrichment carried out at Seversk and the source of uranium in yellowcake from Russia have much higher global warming potential than other supplies. Similar difference can be also seen for the other impact categories: the contribution of enrichment in electricity production from BWR is higher than PWR. This of course is also associated with the total absolute impacts (Table 3.1), which is discussed in more details in the following sub-sections by impact category.

Table 3.1: Environmental Impacts of Baseline Scenario: Total Impacts and Contribution of Front-end Processes (2017)

Impact category	Unit	PWR	BWR	PWR Front-end	BWR Front-end
Climate change	kg CO2 eq	5.6E-03	9.4E-03	58%	72%
Human toxicity, cancer effects	CTUh	7.2E-08	3.5E-08	86%	78%
Human toxicity, non-cancer effects	CTUh	4.7E-09	3.0E-09	97%	94%
Particulate matter	kg PM2.5 eq	3.5E-05	2.1E-05	94%	91%
Ionizing radiation HH	kBq U235 eq	1.8E+00	1.5E+00	90%	49%
Acidification	molc H+ eq	5.7E-05	1.1E-04	75%	87%
Freshwater ecotoxicity	CTUe	7.6E-01	4.1E-01	89%	82%
Land use	kg C deficit	2.2E-02	2.5E-02	61%	63%

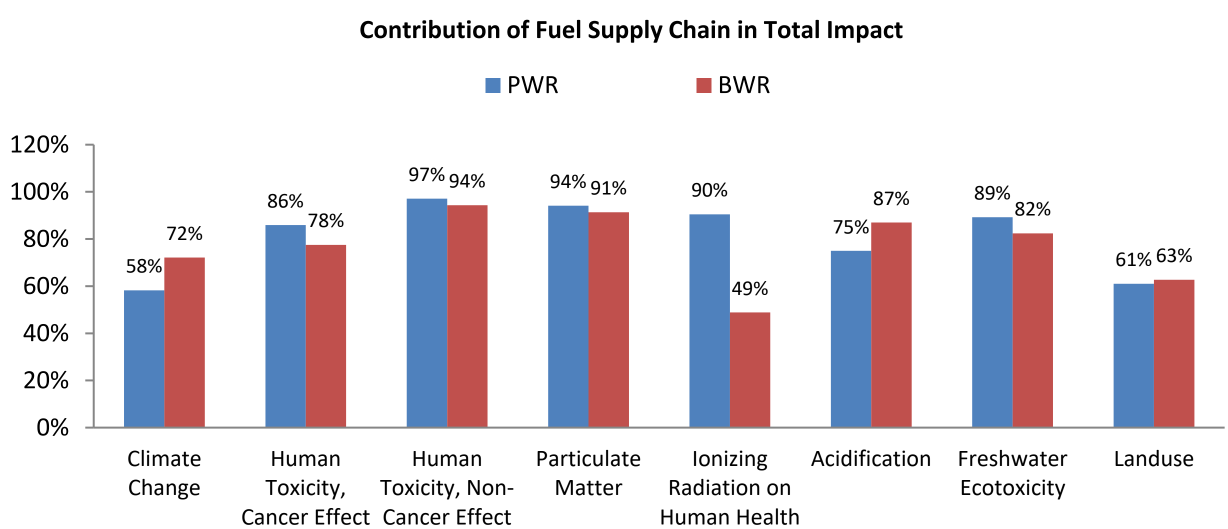


Figure 3.3 Percentage of contribution from fuel supply chain (front-end) to total environmental impacts per kWh generated. Note this is an overview on percentage of contribution by front-end fuel supply chain, or in other words, the sum of impact percentage from uranium mining and milling to fuel

assembly production as shown in Figure 3.1 and 3.2, which show the relative importance of fuel supply chain on different environmental impacts.

Figure 3.3 shows the contribution of front-end fuel processing and supply chain in the life cycle environmental impacts of nuclear power generation; in other words, the contribution of processes before fuel is consumed in the nuclear power plant, including uranium mining and milling, conversion, enrichment and fuel assembly production. The contributions of front-end processes in most of the impacts are more than 50%, except for the ionizing radiation impact from BWR, because the contribution from nuclear power production in BWR has also significant contribution.

3.1.1. Climate Change

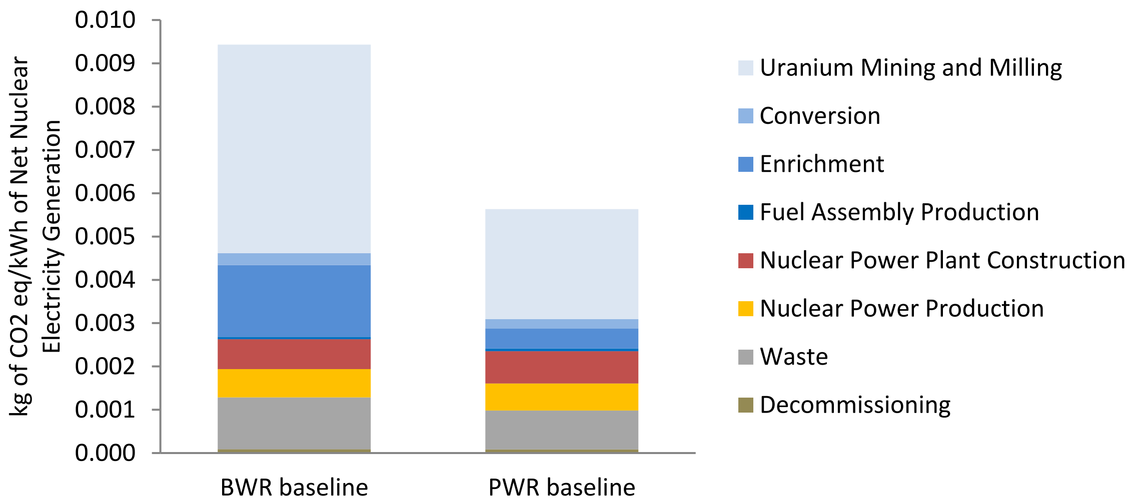


Figure 3.4: Potential impact on climate change for BWR and PWR in the baseline scenario (2017).

The potential impact on climate change is expressed in Global Warming Potential (GWP) in the unit of kg CO_2 equivalent per kWh generated, showing the global warming potential over a time horizon of 100 years.

Figure 3.4 shows the life cycle GHG emissions of electricity production from BWP and PWR in the baseline scenario: ~10 g CO_2 eq/kWh for BWR, and ~6 g CO_2 eq/kWh for PWR. For both BWR and PWR, the results of this study are slightly lower than previously quantified, due to the change in enrichment from diffusion to centrifuge, which is much less energy-intensive (factor of 50-60) than enrichment by centrifuge. These results are also slightly lower than the harmonized, global median lifecycle GHG emissions of nuclear power generation of about 12 g CO_2 eq/kWh (Warner & Heath, 2012).

The main difference between BWR and PWR is caused by the process of uranium mining and milling. 2.5E-5 kg of uranium in yellowcake is required per kWh of electricity production in

BWR, which is more than the 2.3E-5 kg of uranium in yellowcake required per kWh of electricity production from PWR. In addition, the GHG emissions of Russian supply are higher than supplies from Australia (more detailed results in section 3.2). Uranium enrichment for BWR also causes more than three times higher GHG emissions than enrichment for PWR, since the emissions from enrichment at Seversk are much higher (578 kg CO_2 eq/kg SWU) than those of Areva (202 kg CO_2 eq/kg SWU).

3.1.2. Ionizing Radiation

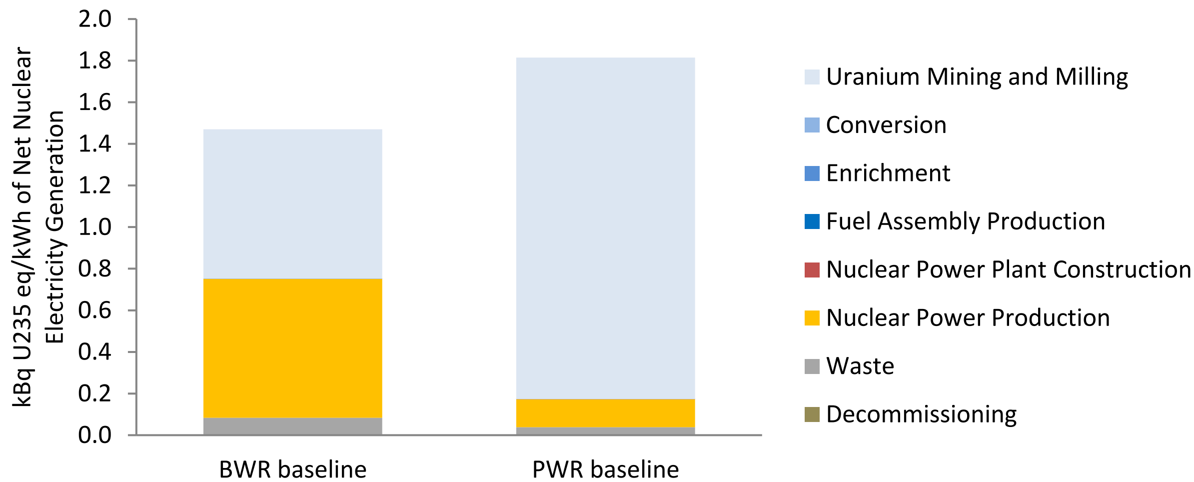


Figure 3.5: Potential impact of ionizing radiation for BWR and PWR in the baseline scenario (2017).

The potential ionizing radiation impact on human health is represented by radioactive emissions in terms of U-235 equivalents, quantified according to the LCIA method developed by Frischknecht et al. (2000), which is based on the Human health effect model as developed by Dreicer et al. (1995). Ionizing radiation also has impacts on ecosystems, but ILCD (Hausschild et al., 2011) does not recommend any impact method for it and therefore, only potential ionizing radiation impact on human health is included here.

The main contribution to ionizing radiation on human health is from uranium mining and milling, which is mainly caused by the treatment of tailings from uranium mining and milling, for which the amount is determined by the uranium concentration in the mined ore (in case of conventional mining). Although the uranium in yellowcake required per kWh of electricity production from PWR is lower than that of BWR, PWR has higher ionizing radiation impact associated with per kg of uranium in yellowcake, which results in higher impact per kWh of electricity production.

Table 3.2: Ionizing radiation impact on human health and related key results

Parameter	Unit	PWR	BWR
Amount of uranium in yellowcake required per kWh of net electricity production	kg U in yellowcake/kWh	2.3E-5	2.5E-5
Ionizing radiation impact from consumption of uranium in yellowcake per kWh of net electricity production	kBq U_{235} eq/kWh	1.64	0.72
Ionizing radiation impact per kg of U in yellowcake	kBq U_{235} eq/kg U	7.15E4	2.87E4

In the case of BWR, the contribution from the nuclear power plant operation is also substantial due to the emissions at the plant, which were updated in this analysis: the emissions of carbon-14 to air per kWh of net electricity production for BWR are about 5 times higher than the emissions from PWR, and in addition, there are emissions of cobalt-60, cesium-134 and -137 to water which are not reported for PWR. These differences result in the comparatively high impact of ionizing radiation on human health for the BWR. It should be noted that the overall ionizing radiation impact on human health might be a bit underestimated, because there is limited data available in the processes of uranium processing and fuel manufacturing: the data on radiation impact reported by the corresponding facilities is available, but usually reported in human exposure; in other words, in measured dose (in Sv) instead of emissions (in Bq). The latter is however required for estimating the potential ionizing radiation impact in LCA, and exposure cannot be easily converted into emissions without knowing more details concerning the measurement, which are not available.

3.1.3. Acidification

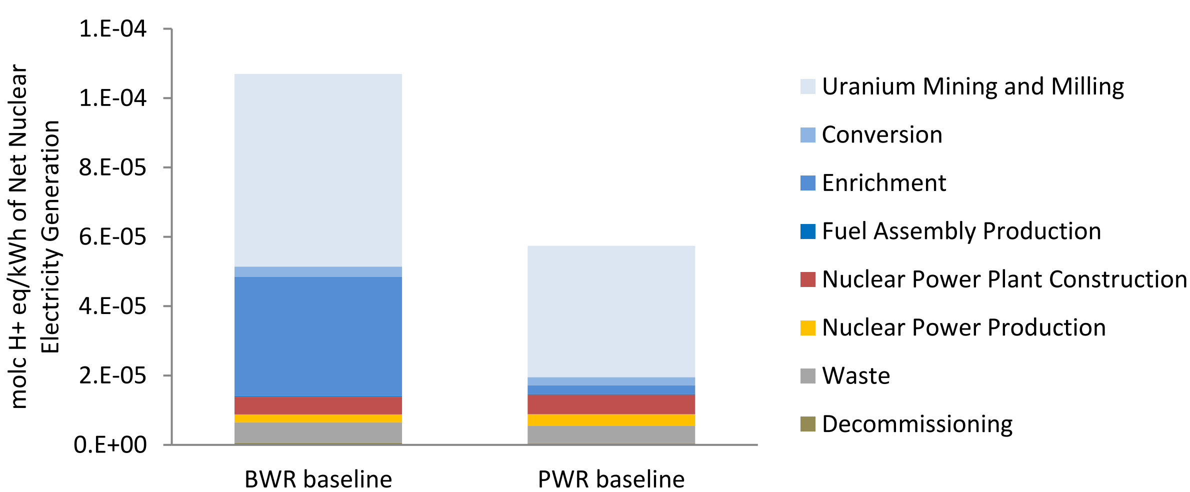


Figure 3.6: Potential impact of acidification for BWR and PWR in the baseline scenario (2017).

To estimate the potential impact of acidification on ecosystem quality, the method developed by (Posch et al., 2008; Seppälä et al., 2006) is applied. The result shows the Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. It can be seen that the enrichment process for PWR causes lower acidification than enrichment for BWR, since the enrichment in Russia has relatively high emissions of ammonia, nitrogen oxides and sulfur dioxide. Uranium mining and milling also has significant contribution to acidification, due to its fuel consumption, and usage of acid chemicals in purification. Uranium in yellowcake from Russia causes comparatively higher potential acidification impacts due to high consumption of heat, chemicals as well as the construction of mining and milling infrastructure.

3.1.4. Human Toxicity

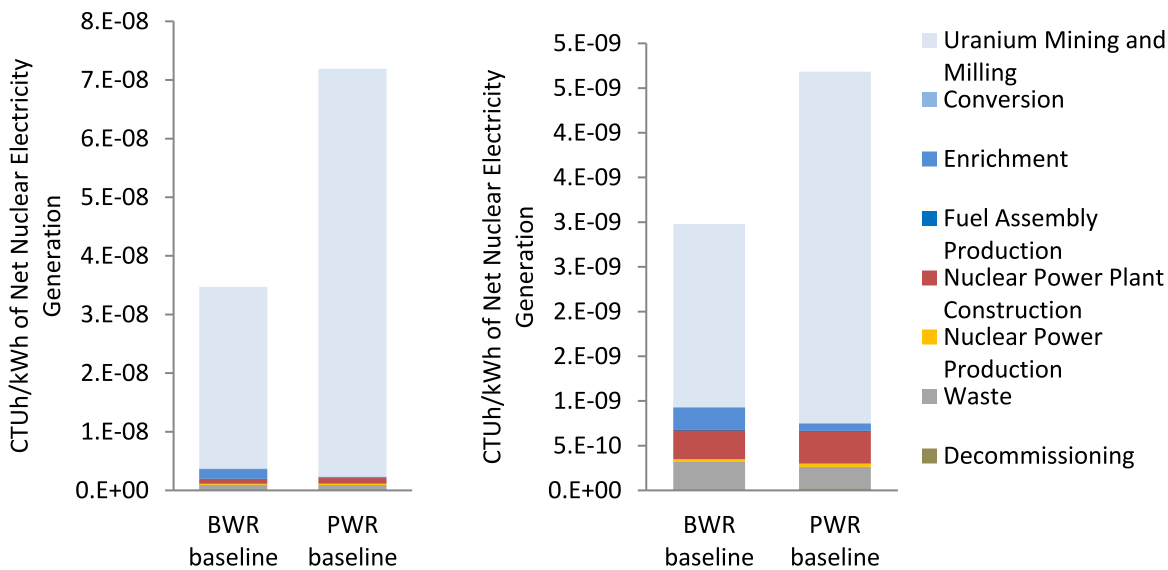


Figure 3.7: Potential impact of human toxicity, non-cancer effects (left) and cancer effects (right) for BWR and PWR in the baseline scenario (2017).

Human toxicity is expressed in Comparative Toxic Unit for humans (CTUh), which shows the estimated increase in morbidity in the total human population per unit mass of a substance emitted, using the method from USEtox (Rosenbaum et al., 2008). The impact is separated into non-cancer effect (left) and cancer effect (right). In non-cancer effect human toxicity, uranium mining is the largest contributor because of the treatment of tailings, and the contributions from other processes are negligible. In human toxicity cancer effect, uranium mining and milling also has the highest contribution for both PWR and BWR from tailing treatment. This is followed by the nuclear power plant construction and nuclear waste treatment due to the consumption of steel. In both impacts, the highest contribution from uranium mining is caused by the tailing treatment and disposal. Tailing generation depends on ore grades of the mined ores, and is different from country to country. More details on this can be found in section 3.2.

3.1.5. Particulate Matter formation

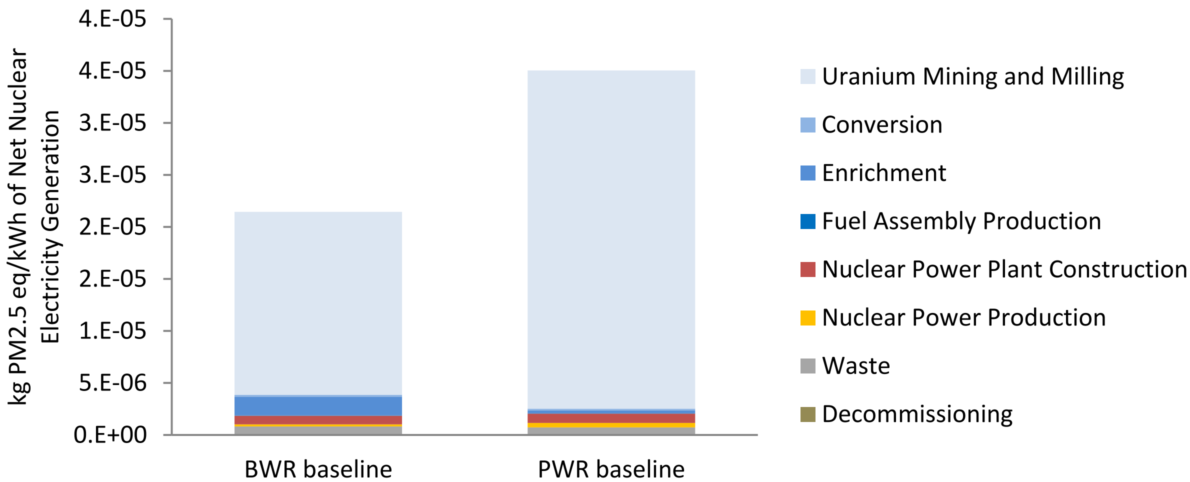


Figure 3.8: Potential impact of particulate matter for BWR and PWR in the baseline scenario (2017).

Potential impacts of primary and secondary particulate matter emission are expressed in the equivalents of fine particles with a diameter of 2.5 µm or less (PM 2.5). PM 2.5 is a concern for human health when levels are high. The tailing treatment in uranium mining and milling is associated with the emissions of particulate matter, and contributes more than 80% of the life cycle particulate matter emissions of the nuclear power generation. The particulate matter emissions in uranium mining and milling is again country-specific, and related to the ore grade of different mining sites. More details on this are provided in section 3.2. Enrichment, especially in the fuel supply for BWR, also contributes to the particulate matter emissions, and it comes from the emissions of particulates from enrichment at Seversk. Its contribution however is much lower than uranium mining and milling process.

3.1.6. Freshwater Ecotoxicity

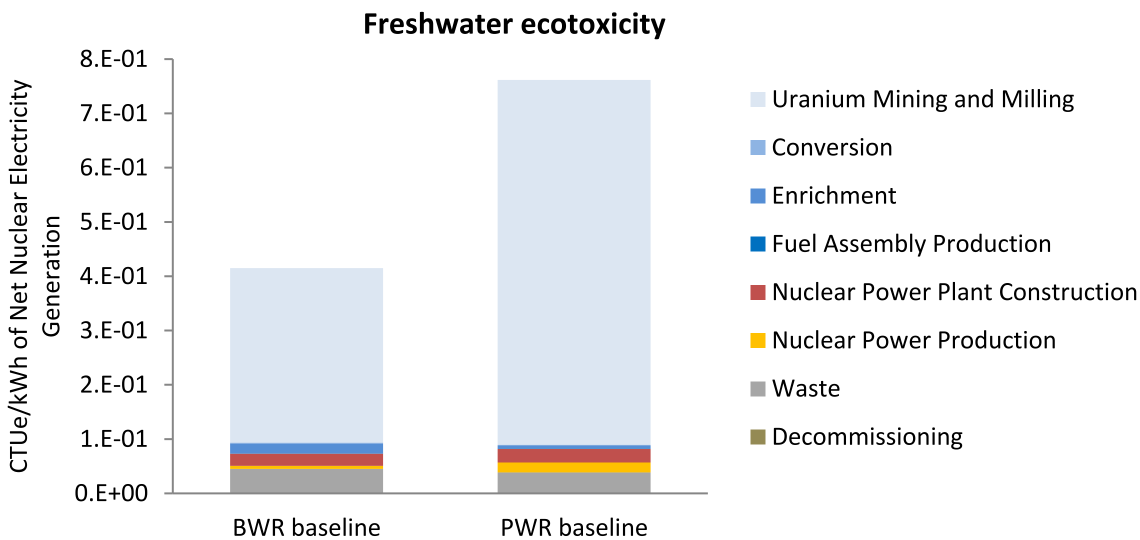


Figure 3.9: Potential impact of freshwater ecotoxicity for BWR and PWR in the baseline scenario (2017).

The potential impact of freshwater ecotoxicity is expressed in Comparative Toxic Unit for ecosystems (CTUe), which represents an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a substance emitted. The impact of freshwater ecotoxicity also mainly comes from the emissions during uranium mining and milling.

3.1.7. Landuse

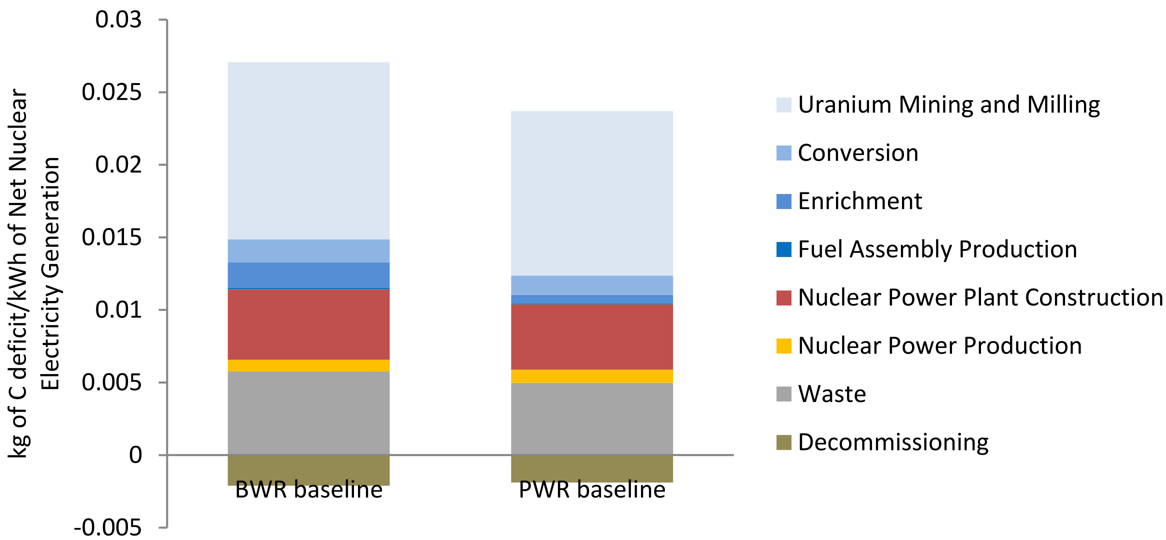


Figure 3.10: Potential impact due to land use for BWR and PWR in the baseline scenario (2017).

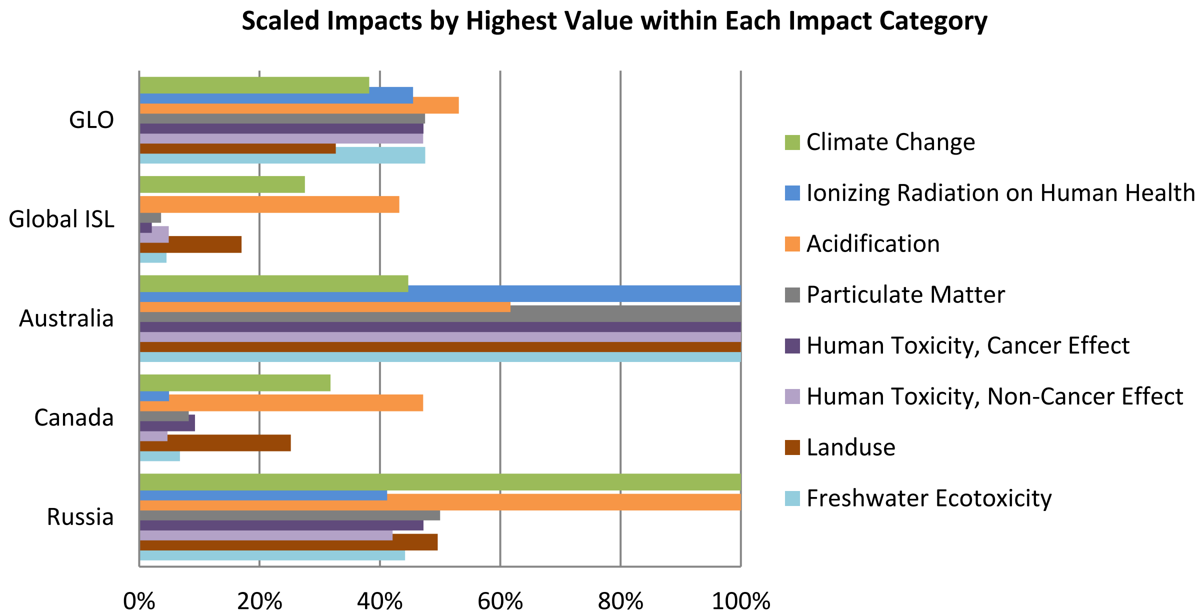
The potential impact of land use is shown in changes of soil organic carbon, measured in kg of carbon deficit. Uranium mining and milling has the largest contribution in land use: about 40% of the land use impact is caused by it, and it mainly comes from uranium tailing treatment. Other than the land use required for tailing treatment, the energy consumption in uranium mining and milling also has indirect impact on land use, in particular in the production of heavy fuel oil and diesel. Well construction in these petroleum product productions requires the transformation of land. Waste is the second largest contributor to land use, since the disposal and storage of waste in geological repository requires space and thus results in impact on land use. In addition, there is impact on land use from the infrastructure of nuclear power plant. Decommissioning of nuclear power plant causes some negative impact in land use, because of the recovery of land from industrial and other uses.

In summary, section 3.1 shows the contributions of fuel supply chain (i.e. uranium mining and milling, enrichment, conversion, and fuel assembly production), plant operation and construction, nuclear waste processing and treatment, and decommissioning for six environmental impact categories. Among these contributions, only plant operation and construction is determined by the type of nuclear plant (i.e. BWR or PWR). The results show that for most of the environmental impacts, significant contributions to the impacts result from the supply chain of fuel, which is independent of the type of nuclear plant. The only impact where plant operation contributes significantly is the impact of ionizing radiation on human health.

3.2. Uranium Mining and Milling

As can be seen from the results above, uranium mining and milling plays a crucial role in almost all impacts included in this study and therefore, a more in-depth analysis is performed for these processes, to compare the performance of country-specific mining and milling sites, as well as to understand the more specific reasons that drive these high impacts.

Figure 3.11 shows the relative environmental impacts of 1 kg of uranium in yellowcake, mined and milled in different regions and from in-situ leaching globally. The impacts are scaled by dividing with the highest impact in each category, so that the worst-performing country has a relative impact equal to 100% (for each indicator). According to available data, uranium in yellowcake produced in Australia has highest potential impacts concerning ionizing radiation on human health, particulate matter, human toxicity cancer effect and non-cancer effect, and freshwater ecotoxicity, due to the amount of tailing treatment, which is associated with lower ore grade in compared to other countries. The potential impacts of supply from Russia are highest in terms of climate change and acidification. The global average in-situ leaching of uranium has a relatively low potential impact on human toxicity, both non-cancer effect and cancer effect, while climate change, acidification and land use scores are comparatively higher but not among the highest in comparison with conventional mining and milling in other countries. The conventional mining and milling in Canada has similar performance as global in-situ leaching, while global average conventional mining and milling stands in the middle among the others.



Notes:

- “GLO” represents the impacts of global average production of uranium in yellowcake, with percentage of country contribution shown in section 2.2.4.1.

- “Global ISL” represents in-situ leaching of uranium globally

Figure 3.11: Scaled potential impacts of uranium mining and milling by country.

To better understand the reasons behind these potential impacts by country, factors that drive the LCIA results are categorized into three groups (shown in Table 3.3), based on the contribution analysis of processes in each impact category (Appendix).

Table 3.3: Factors in uranium mining and milling and their associated potential environmental impacts.

Factors in uranium mining and milling	Associated environmental impacts
Tailing treatment	Ionizing radiation on human health Particulate matter Human toxicity, cancer effect Human toxicity, non-cancer effect Freshwater ecotoxicity
Consumption of chemical **Consumption of energy** **Construction of uranium mining and milling infrastructure**	Climate change Acidification
Construction of uranium mining and milling infrastructure	Land use

To get an overview of all environmental impacts of uranium in yellowcake production by country, and also to validate the grouping of these cause factors, all the environmental impacts are scaled by using the formula below.

$$\text{Normalized } X_{ij} = \frac{X_{ij} - \text{Min}\, X_{ij}}{\text{Max}\, X_{ij} - \text{Min}\, X_{ij}}$$

where i is the impact category, and

j is country, global mix of uranium in yellowcake, or global in-situ leaching.

The difference between each impact and the minimum value of that impact is divided by the difference between the maximum and minimum value of all countries for each impact. The scaling helps to eliminate the absolute value difference between different impact categories. With this scaling, the best-performed country is assigned with a value of 0, while the worst-performed country with a value of 1. These scaled values are then assumed to be equally weighted (each with weighting factor of 0.125, as there are 8 impacts in total), and added up for each country, as shown in Figure 3.12.

The impacts are also colored in three different color schemes depending on the group of cause factor they are assigned with. Based on equal weighting of impact categories, Australia has the highest overall environmental impact among all the countries, followed by conventional mining and milling in Russia, for global average, and in Canada, while uranium in yellowcake produced from in-situ leaching has the least overall impact. The large portion of impacts associated with the tailing treatment indicates that the ore grade of the mined uranium (and the proportional amount of tailings to be treated) is decisive for the country-specific overall environmental performance of uranium mining. This is subject to great uncertainty because the detailed emissions and waste data for uranium and mining is missing, and the data for Russia is also highly uncertain.

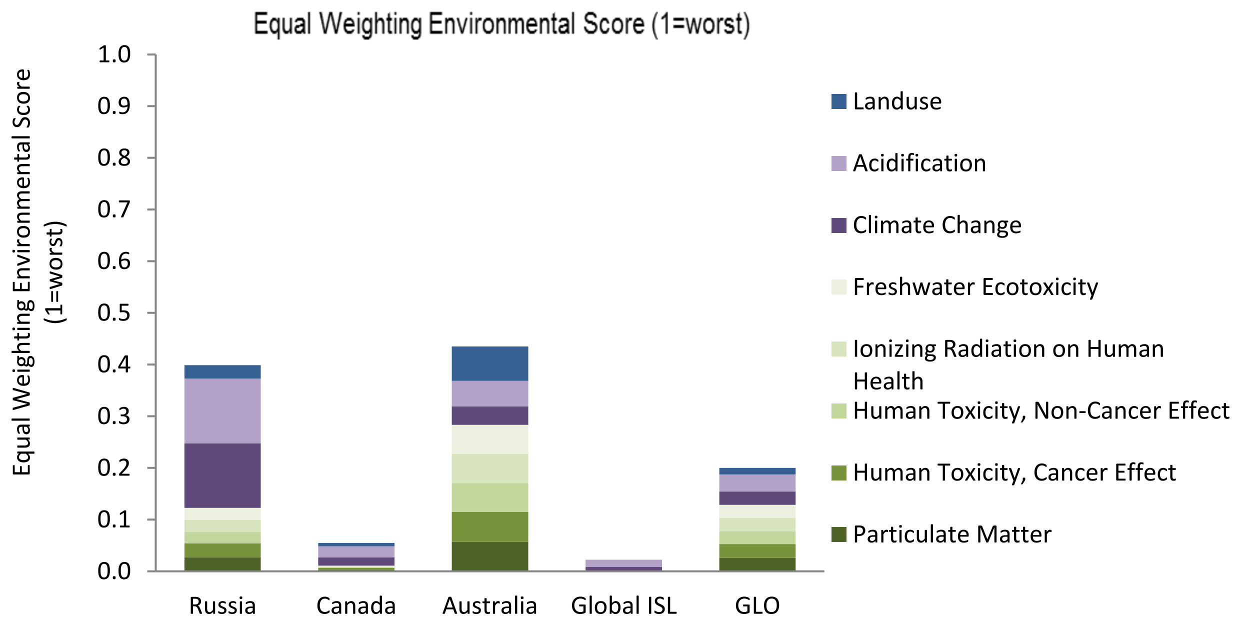


Figure 3.12: Evaluation of uranium mining and milling in different countries with equally weighted impact categories for an aggregated environmental score (1=worst); impacts colored in green: driven by tailing treatment; impacts colored in purple: driven by consumption of chemicals, energy and the construction of infrastructure; impacts colored in blue: driven by construction of infrastructure only.

3.3. Comparison with other electricity generation technologies

Potential environmental impacts of nuclear power are compared with other power supply technologies for Switzerland. The generation technologies covered include: electricity produced from photovoltaics, wind turbines, natural gas, hard coal (import from Germany), and hydro power (both from hydro plants with dams and run-of-river technology). The impacts of other electricity generation technologies are estimated using the datasets from ecoinvent version 3.3 (ecoinvent, 2014), except for the combined cycle power plant consuming natural gas, which is derived from a gas power plant in Germany from ecoinvent version 3.2 (ecoinvent, 2016), with modified natural gas supply for Switzerland. The names of datasets from ecoinvent used for comparison are listed in Table 3.4.

Table 3.4: List of other power generation technologies used for comparison with nuclear electricity production.

Legend in chart	Ecoinvent version 3.3 dataset name
PV slanted roof ins. multi-Si	Electricity, low voltage {CH}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted
PV slanted roof ins. mono-Si	Electricity, low voltage {CH}| electricity production, photovoltaic, 3kWp

	slanted-roof installation, single-Si, panel, mounted
Wind, onshore, <1 MW	Electricity, high voltage {CH}| electricity production, wind, <1MW turbine, onshore
Wind, onshore, 1-3 MW	Electricity, high voltage {CH}| electricity production, wind, 1-3MW turbine, onshore
Hydro, run-of-river	Electricity, high voltage {CH}| electricity production, hydro, run-of-river
Hydro, alpine reservoir	Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region
Natural gas combined cycle plant	electricity, high voltage {DE}| electricity production, natural gas, combined cycle power plant (from ecoinvent v3.2), with modified supply of natural gas from Natural gas, low pressure {CH}
Hard coal (DE)	Electricity, high voltage {DE}| electricity production, hard coal

Figure 3.13 shows the relative potential environmental impacts of these electricity generation technologies; absolute LCIA results per kWh generation can be found in Appendix 5.2. Under each impact category, the impact is scaled using the highest impact among technologies as maximum, so that the technology with highest impact is equivalent to 100%. It is shown that nuclear electricity has much lower life cycle GHG emissions in comparison with electricity produced from fossil fuels (natural gas and hard coal). Life cycle GHG emissions are in the same range as those of hydro power, and both these two technologies exhibit the lowest GHG emissions. In human toxicity, cancer effect, hydro power, wind power, and power from combined cycle gas plant have lower impact than nuclear power. Human toxicity, non-cancer effect, look slightly different: wind power and power production from hard coal and photovoltaics cause higher potential impacts than nuclear power, while hydropower is the only technology that has lower impact. For particulate matter formation, only power from photovoltaics and wind perform better than nuclear power. Nuclear electricity has substantially higher potential impacts in terms of ionizing radiation on human health in comparison with other technologies, because of the mining and milling of uranium to produce yellowcake, which is the source of uranium for nuclear power plant operation. Concerning acidification, nuclear power has much lower potential impacts than power generations from fossil fuels and photovoltaics, and slightly lower than wind power, but higher than hydro power. Regarding freshwater ecotoxicity, potential impacts of nuclear power are much lower than electricity from photovoltaics, small-scale onshore wind turbines, and hard coal power plant. Land use of nuclear power is in the lower range compared to other electricity generation technologies, but higher than that of hydro power.

In Figure 3.14, the potential variations of impacts of nuclear electricity generation are shown, considering the uncertainty ranges of modeling choices, because these are the most sensitive assumptions resulting in the widest ranges of potential impacts. The worst-case scenario is represented considering uranium supply from Russia (see more details in section 3.4.2). The highest variation is shown for the impact of ionizing radiation on human health, which shows that when the supply of uranium in yellowcake is supplied by origin with high radiation impact in uranium mining and milling (resulting from a low ore grade), the impact can increase substantially. On the other hand, even in the best-case scenario, the ionizing radiation impact of nuclear electricity generation is higher than the impact of other electricity generation technologies. High variability can also be observed for the impacts of human toxicity, which shows in the best-case scenario a substantial reduction, and perform better than some other electricity generation technologies, while in the worst-case scenario, these impacts for nuclear power become higher than all other technologies. Variability of LCIA results of nuclear power for other impact categories due to modeling choices is comparatively low, especially in climate change, acidification and land use, in which almost no variability can be observed in compared to other technologies. However, it should be kept in mind that the impact assessment methodologies have relatively high uncertainty, and the inventory data itself has also uncertainties, which are both not considered here. The conclusions above are also made without considering the impact uncertainty ranges of other electricity generation technologies.

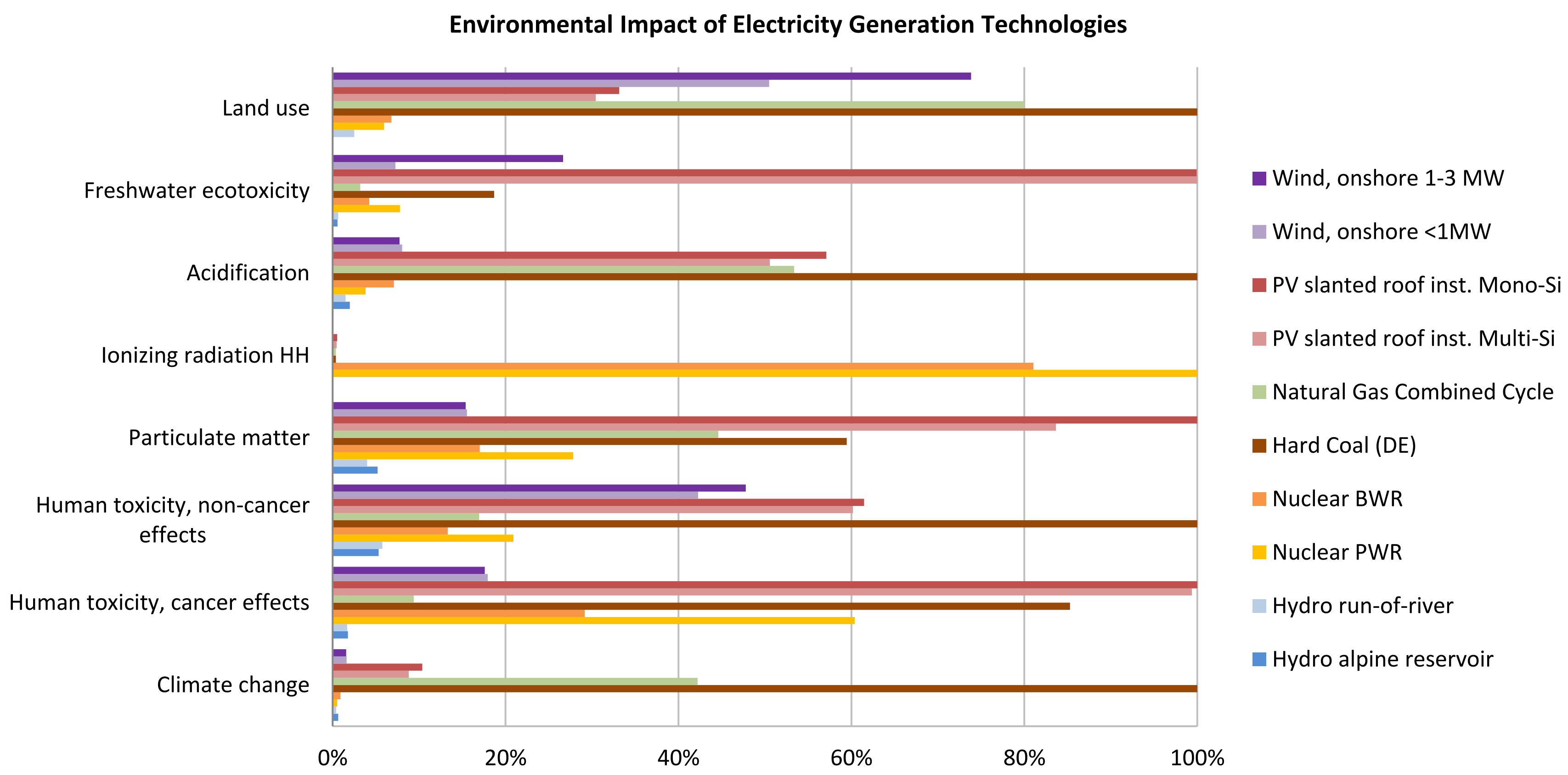


Figure 3.13: Comparison of potential environmental impacts of different electricity generation technologies for Swiss supply, per kWh of electricity generated at the power plant.

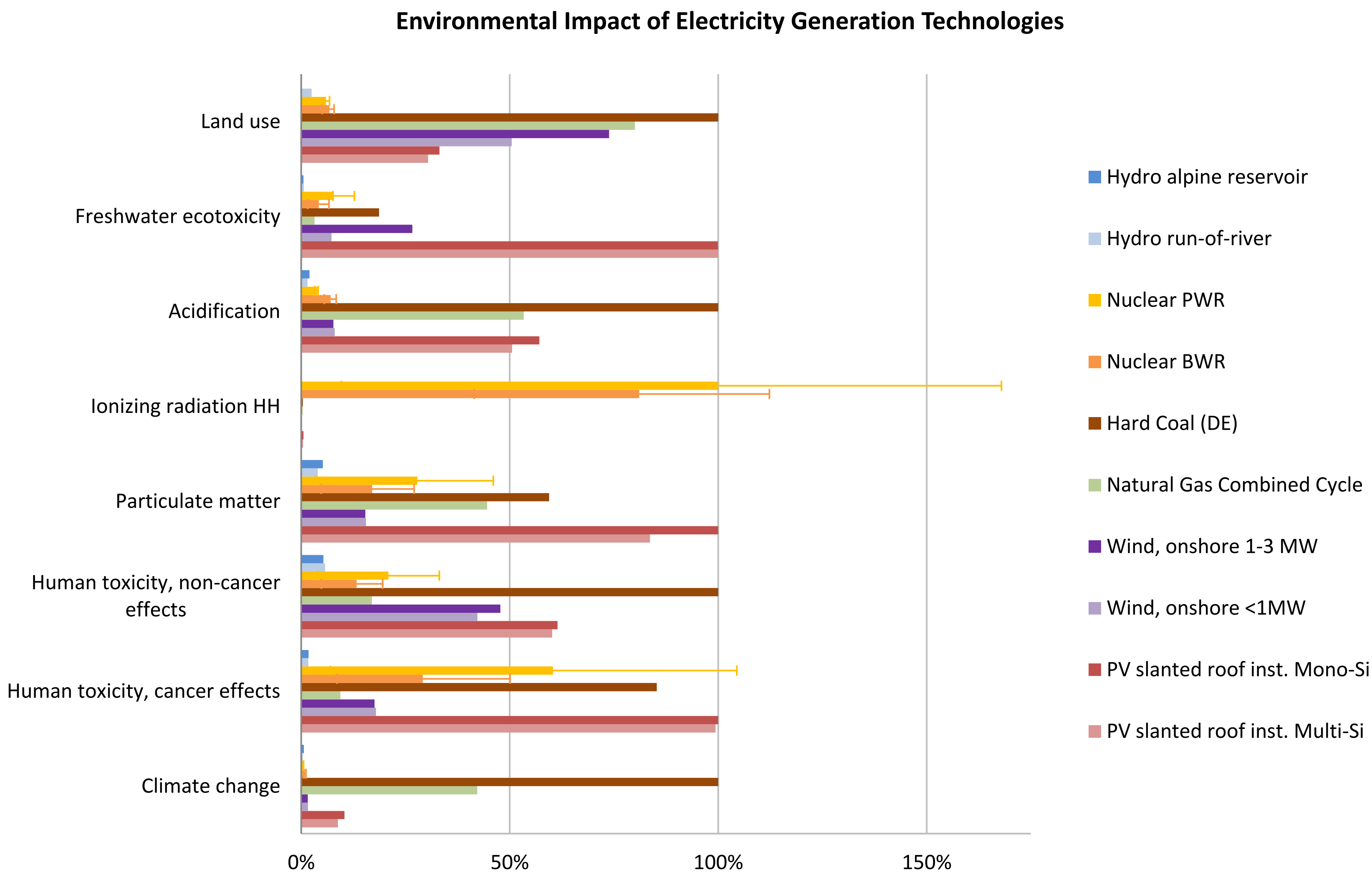


Figure 3.14: Comparison of potential environmental impacts of different power generation technologies for Swiss supply, per kWh of electricity generated at the power plant; with nuclear electricity generation error bars considering the variability due to modeling choices (section 3.4.2).

3.4. Sensitivity Analysis

3.4.1. Sensitivity of reference data year

Variation of reference data year concerns fuel supply (to a limited extent), power plant operation, as well as waste generation and disposal (see Table 2.18). Consistent and complete historical data for processes such as conversion, enrichment and fuel assembly production are not available. There are two options of reference years used in deriving LCI: one using data – as recent as available ("short-term option", representing operation in 2017), and another using as long-term historical data as possible ("long-term option"). Even if the consistency of this analysis is limited to a certain extent due to non-homogenous data availability (i.e. not all processes in the nuclear chain have these two options of reference data year), the results provide an idea whether this kind of temporal variation in compiling LCI data causes substantial differences in LCIA results.[12] The resulting difference can be seen in Figure 3.15, expressed by the scaled impact based on short-term and long-term reference data. The scaling is performed by using the absolute impact divided by the maximum impact under each impact category. The resulting differences in potential impacts between these two options of reference years are between 2% and 61%, corresponding to the lowest sensitivity of reference data year in climate change, and the highest sensitivity of reference data year in human toxicity cancer effect, respectively.

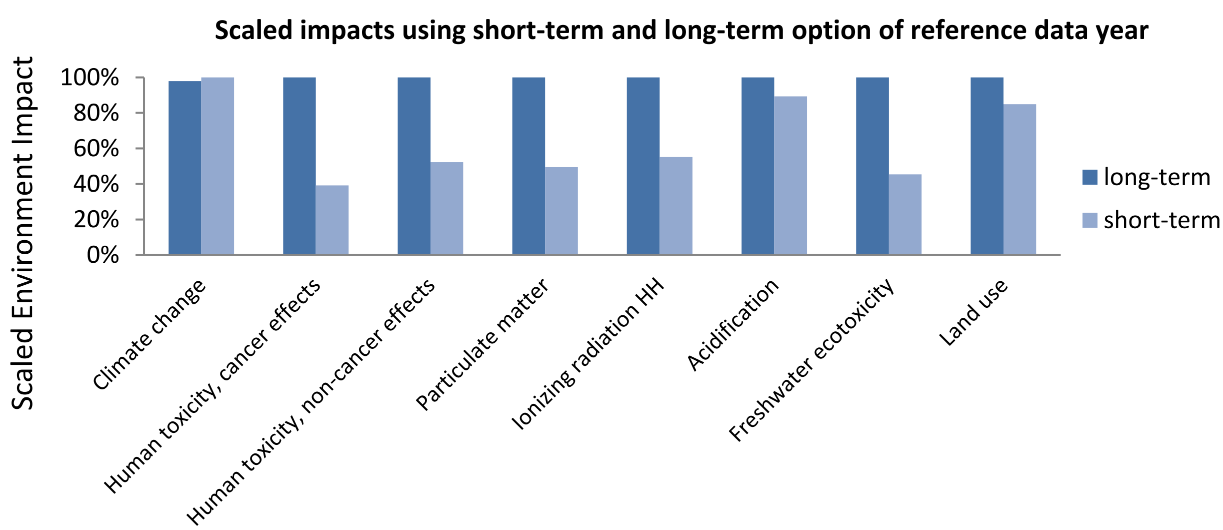


Figure 3.15: Scaled environmental impacts using short-term and long-term option of reference data year.

[12] This analysis only concerns foreground processes of the nuclear power generation chain, as listed in Appendix; ecoinvent v3.1 representing current processes and technologies always serves as source of background LCI data (e.g., for electricity supply, steel production, transport services, etc.).

In order to understand the contribution of processes in causing these differences in impacts, the difference caused by each nuclear chain process is divided by the total difference under each impact category, and their contributions are shown in Figure 3.16 below.

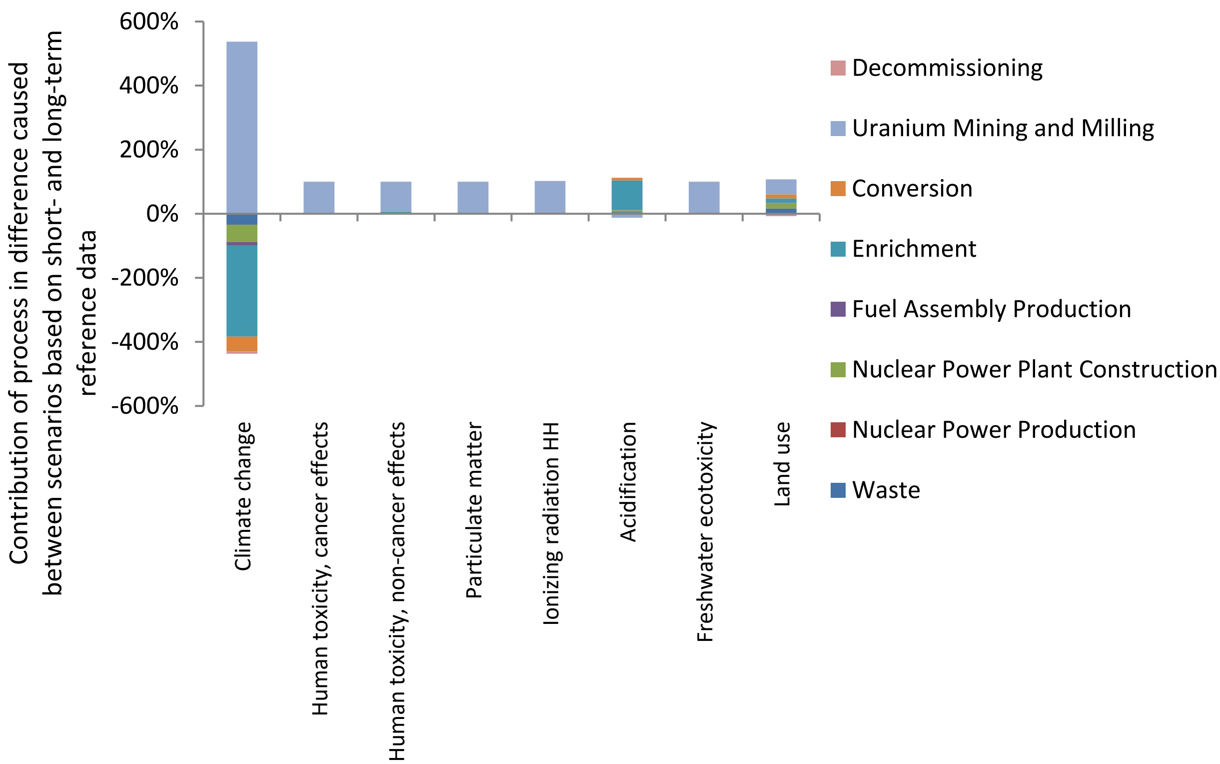


Figure 3.16: Contribution of nuclear chain processes based on different reference data year in causing the difference on environmental impacts.

Contributions of differences from processes that don't have two options of reference data year can be also seen, because the amounts of nuclear power production are different between these two scenarios and therefore, the burdens per kWh from all processes are different. Although this parameter is shown under process of nuclear power production, it causes difference in terms of fuel consumption, which further leads to difference in upstream processes in the fuel supply chain. There are processes with negative contributions, which indicate that the impact differences of these processes exhibit an opposite trend than the overall impact difference.

It shows that most of the differences are caused by two processes: uranium mining and milling, and uranium enrichment. The total difference in terms of climate change impacts is almost negligible, because the positive difference (short term LCI data generating higher GHG emissions than long term LCI data) of uranium mining and milling is almost compensated by the negative difference caused by uranium enrichment and other processes, and this results in a very small total difference. Other than climate change, the differences are dominated by uranium mining and milling, except the difference in acidification, which is mainly caused by uranium enrichment. In general, using short-term LCI data representing nuclear power in 2017 tends to result in lower burdens than the approximated long-term LCI data, which reflects an improvement of the environmental performance of the nuclear chain over time.

3.4.2. Sensitivity of modeling choices

The sensitivities of modeling choices are shown below for Swiss nuclear power production from BWR and PWR, respectively. The impacts are scaled with the impacts of the baseline scenario always to be 100%. It is shown that for impacts on climate change, acidification and land use, much smaller variability caused by modeling choices are shown than for the other impact categories. This is because the contribution from uranium mining and milling in these three impacts are relatively low in compared to other impacts (see section 3.1). Similarly, the results for PWR is more sensitive to modeling choices than for BWR, as the contributions of uranium mining and milling in most of the impacts are higher than that of BWR: up to +/-70% of impacts variation can be observed for BWR, while for PWR, the variation of impacts range from about -90% to +70%.

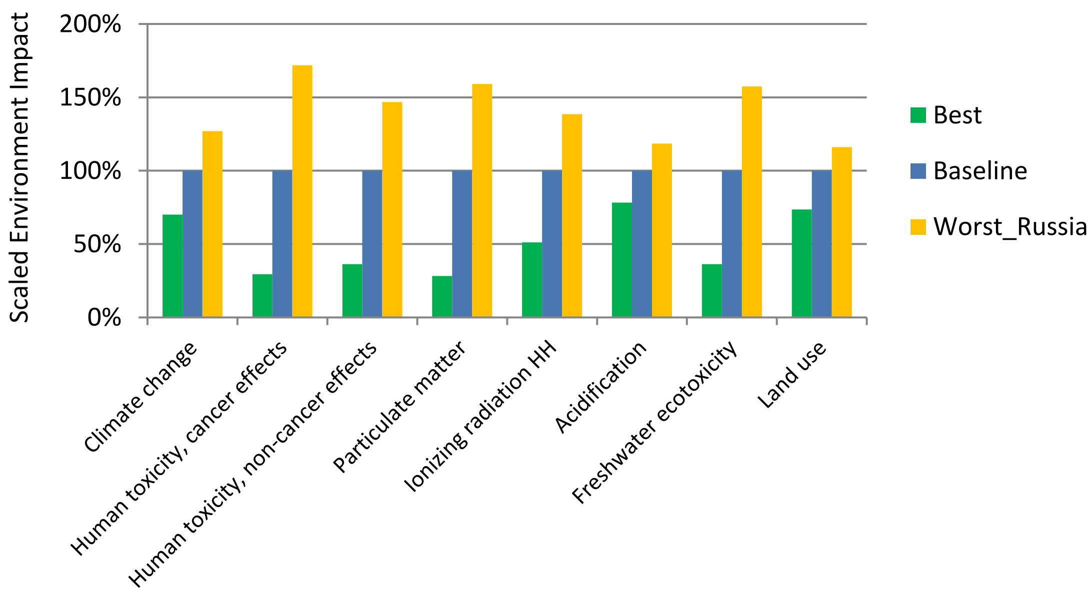


Figure 3.17: Sensitivity of modeling choices on scaled environmental impacts for nuclear power production from BWR.

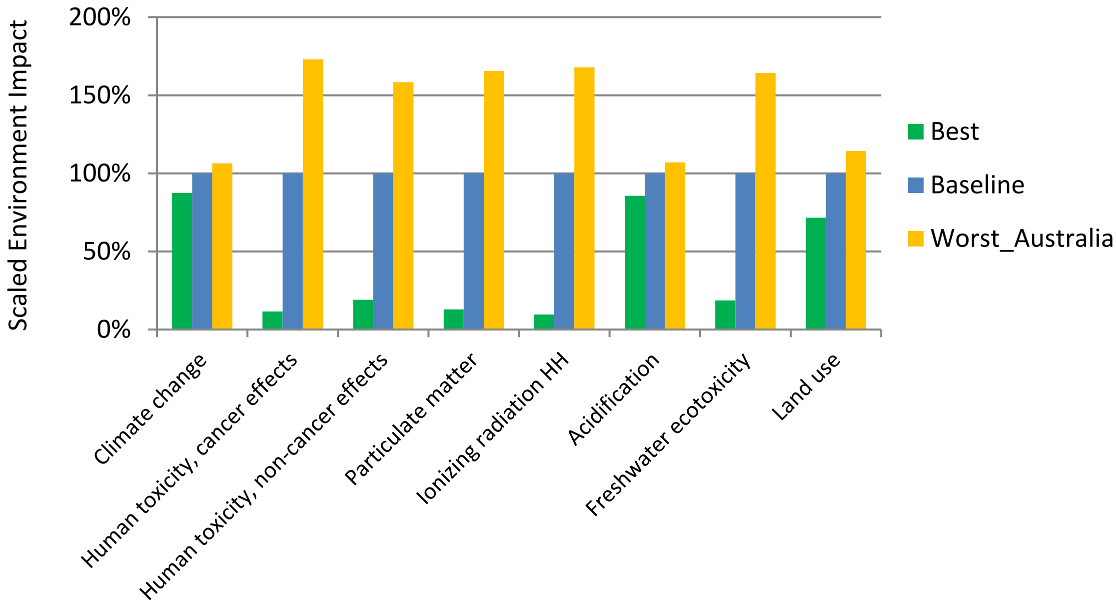


Figure 3.18: Sensitivity of modeling choices on scaled environmental impacts for nuclear power production from PWR.

3.4.3. Sensitivity of key raw data ranges

The sensitivities of raw data ranges are shown below for Swiss nuclear power production from BWR and PWR, respectively. In general, it shows that all the ranges of raw data selected in this analysis cause less than 20% variation on the environmental impacts, and the performance of worst scenario is almost the same as the performance of baseline scenario. Up to 20% of improvement in all impacts however is shown comparing best scenario with baseline scenario.

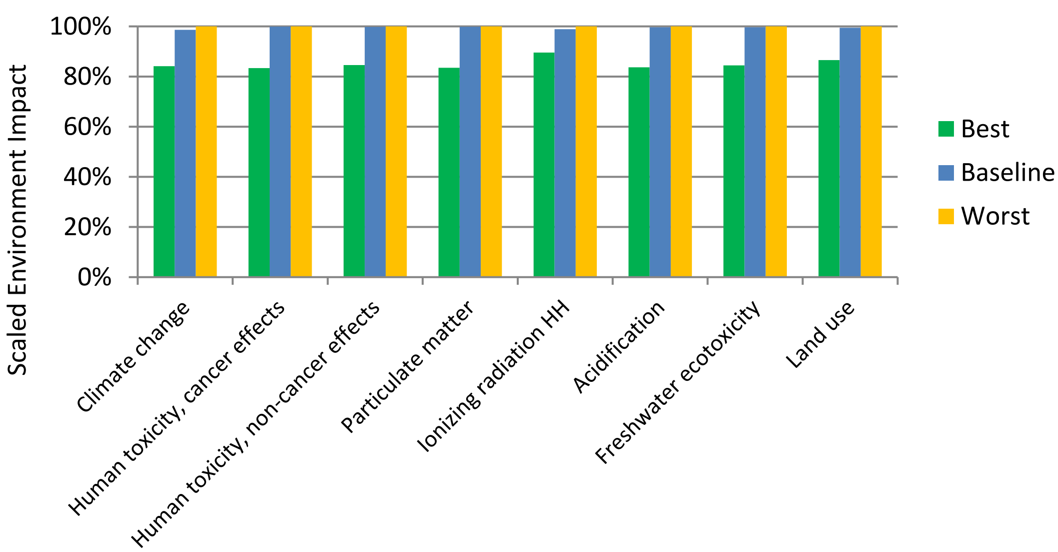


Figure 3.19: Sensitivity of raw rata ranges on scaled environmental impacts for nuclear power production from BWR.

The improvement from baseline scenario to best scenario is reduced to less than 10% in the case of nuclear power production from PWR. This is highly related to the close assumptions between baseline scenario and best-case scenario shown in section 2.3.3. The overall variation of environmental impacts caused by ranges of raw data is also much less compared to the variations caused by modeling choices and reference data year.

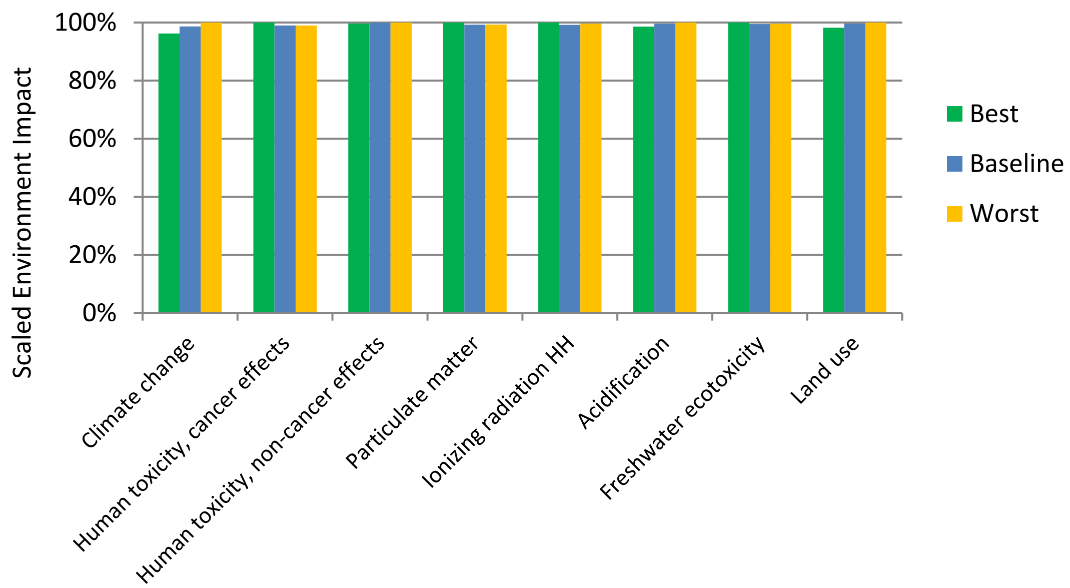


Figure 3.20: Sensitivity of raw rata ranges on scaled environmental impacts for nuclear power production from PWR.

3.5. Prospective Scenarios: LCIA results

The LCIA results of the prospective scenarios are shown in the table below. The potential environmental impacts of Swiss nuclear power in 2020 (according to the scenarios outlined in section 2.3) will be very close to the impacts of the baseline scenario, with less than 5% reduction for all impacts investigated in this study. This can be explained by the slight variation of parameters between baseline and prospective scenarios shown in section 2.3. The reduction of environmental impacts comes only from the fuel supply chain, as increased burnup will decrease the fuel consumption, and increased annual electricity production means less inputs of construction and decommissioning of the nuclear power plants are assigned to each kWh of electricity produced.

Table 3.5: LCIA results for PWR and BWR in prospective scenarios, and percentage of prospective LCIA results compared to baseline LCIA results.

Impact category	Unit	BWR Prospective 2020	PWR Prospective 2020	BWR % of impact of baseline	PWR % of impact of baseline
Climate change	kg CO2 eq	9.2E-03	5.5E-03	98%	97%
Human toxicity, cancer effects	CTUh	2.9E-09	4.5E-09	98%	96%
Human toxicity, non-cancer effects	CTUh	3.4E-08	6.9E-08	98%	96%
Particulate matter	kg PM2.5 eq	2.1E-05	3.4E-05	98%	96%
Ionizing radiation HH	kBq U235 eq	1.5E+00	1.7E-00	99%	96%
Acidification	molc H+ eq	1.0E-04	5.6E-05	98%	97%
Freshwater ecotoxicity	CTUe	4.1E-01	7.1E-01	98%	96%
Land use	kg C deficit	2.4E-02	2.1E-02	98%	98%

4. Conclusion and Outlook

Life Cycle Assessment (LCA) of nuclear power generation in Switzerland with the power plants in Gösgen and Leibstadt – representing PWR and BWR – has been performed for operation and fuel supply in 2017 (representing “current” conditions as baseline); in addition, alternative (including prospective) scenarios were investigated. This LCA provides a comprehensive evaluation of the environmental performance of nuclear power in Switzerland: Eight environmental impact categories are covered in this study, based on their relevance for the environmental impact of nuclear power generation from a life cycle perspective, and the recommendation level provided by the European Commission Joint Research Centre. Compared to the previously available inventory data (LCI) for the Swiss nuclear power generation chains, numerous updates could be implemented in LCI by process in the nuclear chain for BWR and PWR, including the integration of a previous study that investigated the waste handling and storage from Zwilag to geological repository, which PSI performed for NAGRA in 2014 (Fave et al., 2014), and considering the latest information available along all the processes of the nuclear chain. In the baseline scenarios in 2017, the “best-estimate” life cycle GHG emissions of 1 kWh of net electricity production from BWR and PWR (at the power plant) are around 9.4 and 5.6 g of CO_2 equivalents, respectively. These values are similar to previous LCA results quantified by PSI and also similar to international state-of-the-art literature. Most of the impacts are dominated by the impacts from uranium mining and milling, except the impact of ionizing radiation on human health in BWR, where the operation of nuclear power plant also has substantial contribution. Similar contributions by process are shown for BWR and PWR, except in the impact of ionizing radiation on human health, in which the contribution from nuclear power production (i.e. direct emissions from the plant) for BWR is much higher than that for PWR; and in the impact of acidification, the contribution of uranium enrichment for BWR is higher than its contribution for PWR, since the uranium enriched in Russia in BWR's fuel supply chain has comparatively higher emissions of ammonia, nitrogen oxides and sulfur dioxide. In general, the contributions of front-end processes (processes before fuel is consumed in the nuclear power plant) in most of the impacts are about or more than 50%. The environmental impacts of the prospective Swiss nuclear power generation in 2020 are very close to the baseline situation, with less than 5% reduction for all impacts investigated.

Due to the substantial role of uranium mining and milling in almost all the impacts, an in-depth contribution analysis has been performed for this particular process, and the environmental performances of this process between regions were compared. Based on the available data, supply from global in-situ leaching shows the lowest life cycle GHG emissions, and the supply from Russia shows the highest GHG emissions per kg of uranium in yellowcake production. In terms of overall environmental performance, uranium produced from in-situ leaching causes lowest burdens for most impact categories, while supply from Australia (due to the lowest ore grad among the mining sites considered) causes highest burdens for most impact categories. This is because except of uranium produced by in-situ leaching, most impacts of uranium mining and milling are triggered by the treatment of tailings, the amount of which is highly related to the ore grade of the mining sites. This is an assumption applied in this study, and it should be kept in mind that other factors may also affect the amount of tailing that needs to be treated.

Comparing with other power generation technologies for Swiss supply, nuclear power generation shows much lower life cycle GHG emissions than power produced from fossil fuels (natural gas and hard coal), lower emissions than photovoltaics and slightly lower emissions than wind power. Life cycle GHG emissions of nuclear are slightly higher than those of hydropower. In terms of ionizing radiation, nuclear electricity has substantial higher potential impact than the other technologies, mainly due to radiation impact caused by uranium mining and milling to produce yellowcake and the nuclear power plant operation. Further analyzed potential life-cycle impacts of nuclear power are mostly in the lower range of impacts compared to the other technologies included in the comparison.

The results of sensitivity analysis show that the environmental impacts are much more sensitive to the modeling choices and reference data year (i.e. time period represented by LCI data) than the uncertain ranges of the key raw data as well as expected prospective changes in power plant operation and associated fuel supply. In terms of contribution to differences caused by variation in reference data year and modeling choices in comparison to baseline assumptions, uranium mining, milling and enrichment are the most influential processes. The sensitivity analysis of modeling choices – supposed to represent variability in LCA results due to inherent uncertainties and data gaps – shows that, depending on the impact category, the worst-case scenario can have up to about 70% of higher impacts than the baseline scenario.

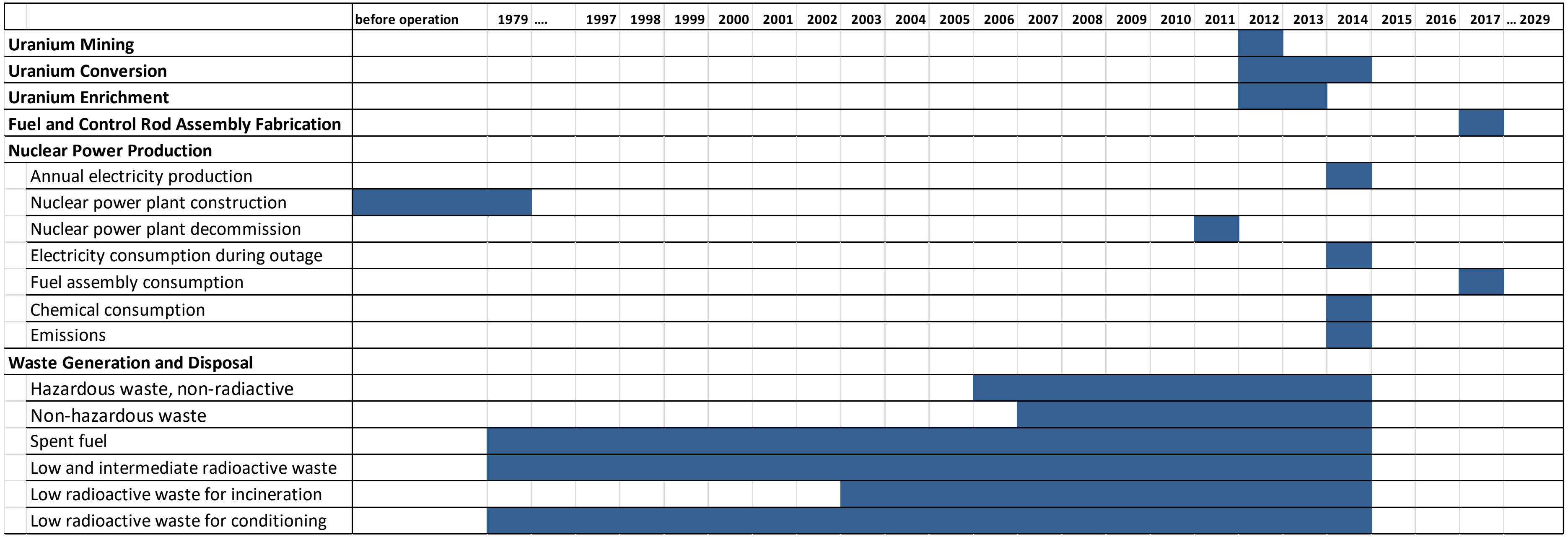
In general, this study can be regarded as a state-of-the-art update and extension of the LCA of Swiss nuclear power for year 2017 (i.e., current conditions) and near-future prospective scenarios. It provides a solid foundation to better understand the Swiss nuclear fuel chain, and to compare nuclear power with other electricity generation technologies. The sensitivity analysis results show how specific processes in the nuclear chain influence the environmental impact of Swiss nuclear generation, and provide quantitative reference for operators to further improve the overall environmental performance of Swiss nuclear power generation. However, due to several data constraints, assumptions and approximations were required, and they need to be further refined in the future when more information is available. Most importantly, the quality of LCI data for supply of uranium from Russia needs to be improved, in particular the origin of the uranium other than produced from conventional mining and milling. This is a relevant part of the fuel supply for KKL and an (unknown) fraction of this uranium originates from reprocessed uranium of diverse sources – complete data for the associated processes are not available to the authors of this report. In addition, all the data assigned with "acceptable" data quality level listed in Table 2.4 need to be refined. Moreover, further prospective scenarios beyond 2020 could be evaluated with more information from the power plant operators in the future.

5. Appendix A

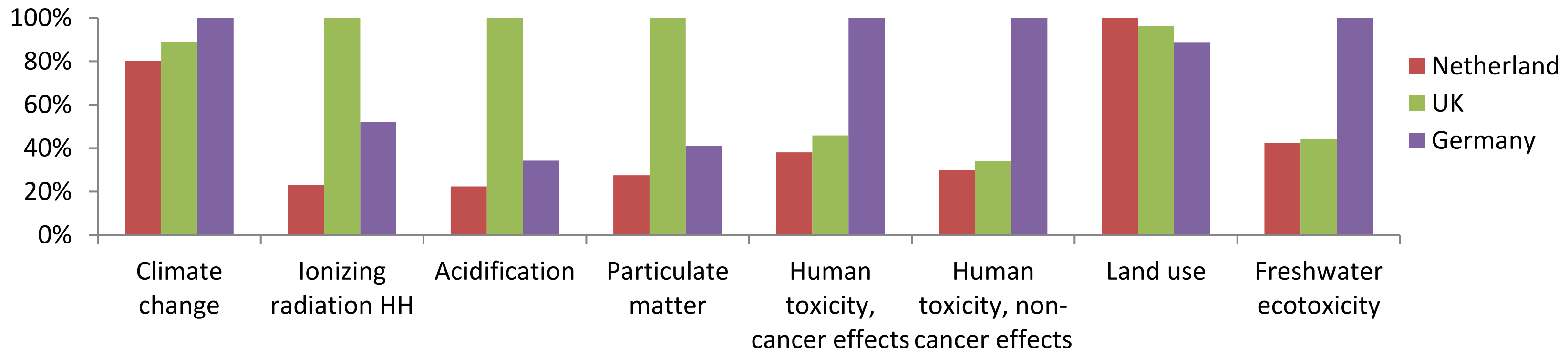
5.1. Treatment of low and intermediate radioactive waste (ion-exchange resins, liquid concentrate, for filter and activated metals) in PWR (KKG)

Data	Value	Unit
Treatment for ion-exchange resins - Electricity demand for drying	800	kWh/drum
Treatment for ion-exchange resins - Electricity demand for bituminization in drum	450	kWh/drum
Treatment for ion-exchange resins - Demand for bitumen per drum	116	kg/drum
Treatment for ion-exchange resins - Demand for nitrogen per drum	unknown	kg/drum
Treatment for ion-exchange resins - kg of ion-exchange resin per batch treatment with nitrogen	180	kg/batch
Treatment for ion-exchange resins - kg of ion-exchange resin per drum	67	kg/drum
Treatment for liquid concentrate - Chemical requirement - Sulfuric acid (Schwefelsäure)	657	kg/a
Treatment for liquid concentrate - Chemical requirement - Caustic soda (Natronlauge)	3600	kg/a
Treatment for liquid concentrate - Chemical requirement - EDTA	25	kg/a
Treatment for liquid concentrate - Chemical requirement - Antifoam (Antischaum)	5	kg/a
Treatment for liquid concentrate - Bitumen requirement per drum	136	kg/drum
Treatment for liquid concentrate - Bitumen requirement per year	4.9	ton/a
Treatment for liquid concentrate - Cement requirement	83.7	kg/drum
Treatment for liquid concentrate - Electricity demand for drying	800	kWh/drum
Treatment for liquid concentrate - Electricity demand for bituminization in drum	450	kWh/drum
Treatment for filter and activated metals - Cement per drum	83.7	kg/drum

5.2. Reference data year of PWR (KKG)



5.3. Scaled environmental impacts of electricity production in UK, US (WECC), Netherlands and Germany



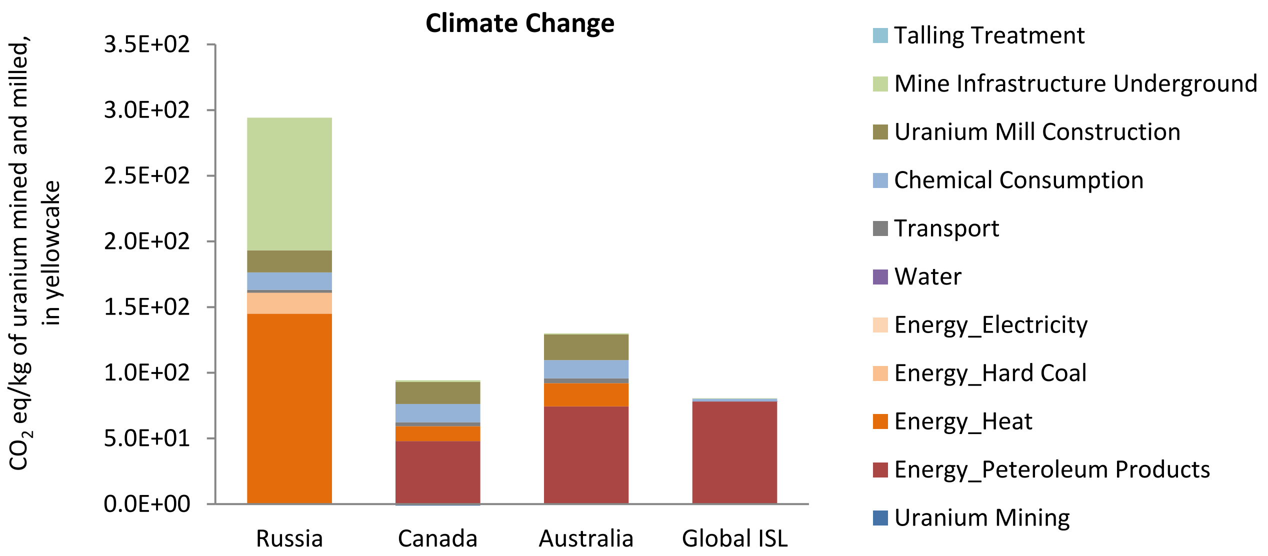
Note: based on medium-voltage electricity production from country market in ecoinvent version 3.3; scaled by dividing the absolute impact by maximum impact of each impact category; worst-performed country is equal to 1.

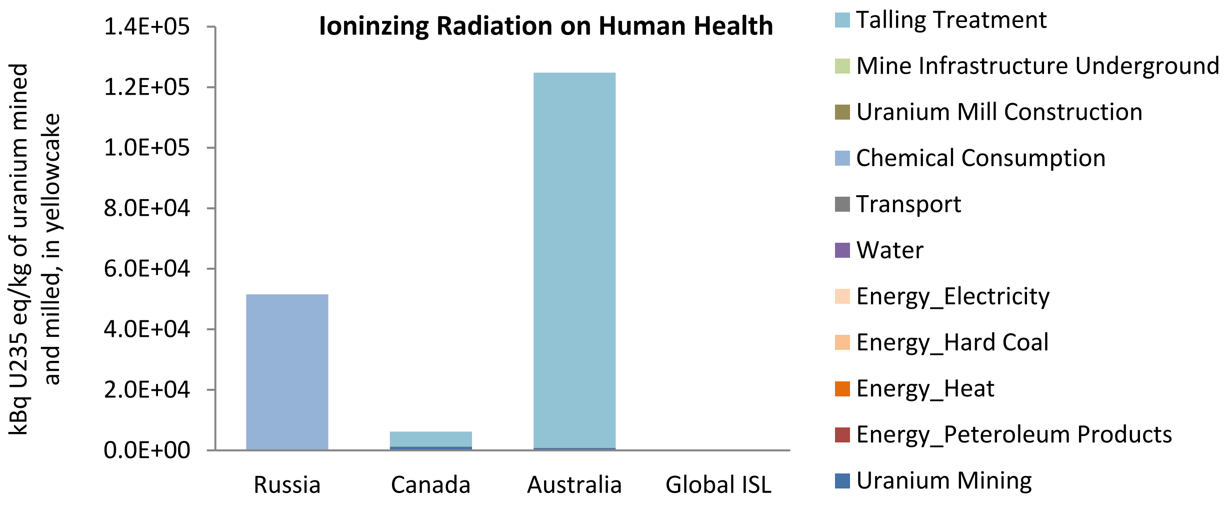
5.4. Absolute environmental impact of electricity generation technologies

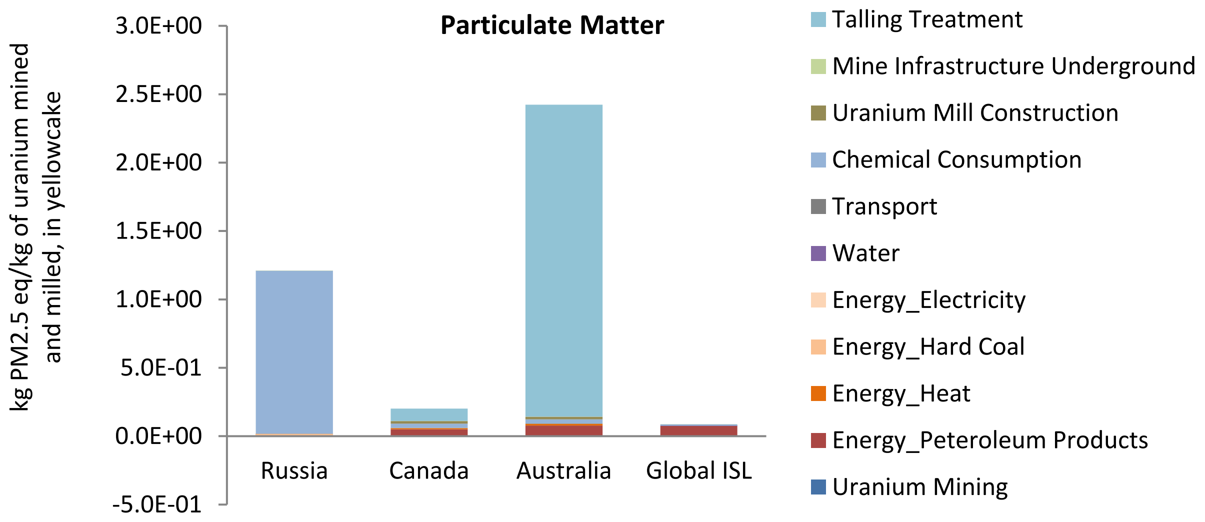
	Unit	Nuclear		PV slanted rood inst.		Wind, onshore		Hydro		Natural Gas Combined Cycle	Hard Coal (DE)
		BWR	PWR	Multi-Si	Mono-Si	<1MW	1-3 MW	run-of-river	alpine reservoir		
Climate change	kg CO2 eq	9.4E-03	5.6E-03	9.2E-02	1.1E-01	1.7E-02	1.6E-02	4.2E-03	6.8E-03	4.4E-01	1.0E+00
Human toxicity, cancer effects	CTUh	3.5E-08	7.2E-08	1.2E-07	1.2E-07	2.1E-08	2.1E-08	2.0E-09	2.1E-09	1.1E-08	1.0E-07
Human toxicity, non-cancer effects	CTUh	3.0E-09	4.7E-09	1.3E-08	1.4E-08	9.5E-09	1.1E-08	1.3E-09	1.2E-09	3.8E-09	2.2E-08
Particulate matter	kg PM2.5 eq	2.1E-05	3.5E-05	1.1E-04	1.3E-04	2.0E-05	1.9E-05	5.0E-06	6.5E-06	5.6E-05	7.5E-05
Ionizing radiation HH	kBq U235 eq	1.5E+00	1.8E+00	8.4E-03	9.7E-03	1.1E-03	8.9E-04	2.6E-04	4.0E-04	6.7E-03	7.0E-03
Acidification	molc H+ eq	1.1E-04	5.7E-05	7.6E-04	8.6E-04	1.2E-04	1.2E-04	2.3E-05	3.0E-05	8.1E-04	1.5E-03
Freshwater ecotoxicity	CTUe	4.1E-01	7.6E-01	9.8E+00	9.8E+00	7.1E-01	2.6E+00	6.4E-02	5.5E-02	3.1E-01	1.8E+00
Land use	kg C deficit	2.5E-02	2.2E-02	1.1E-01	1.2E-01	1.9E-01	2.7E-01	9.2E-03	-2.4E-02	2.9E-01	3.7E-01

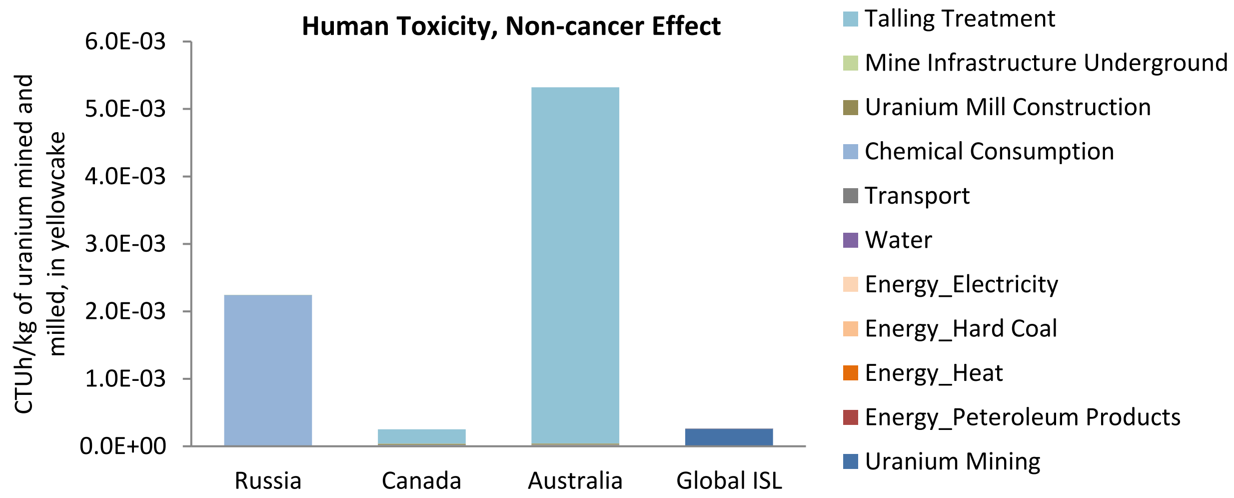
5.5. Contribution analysis of uranium mining and milling

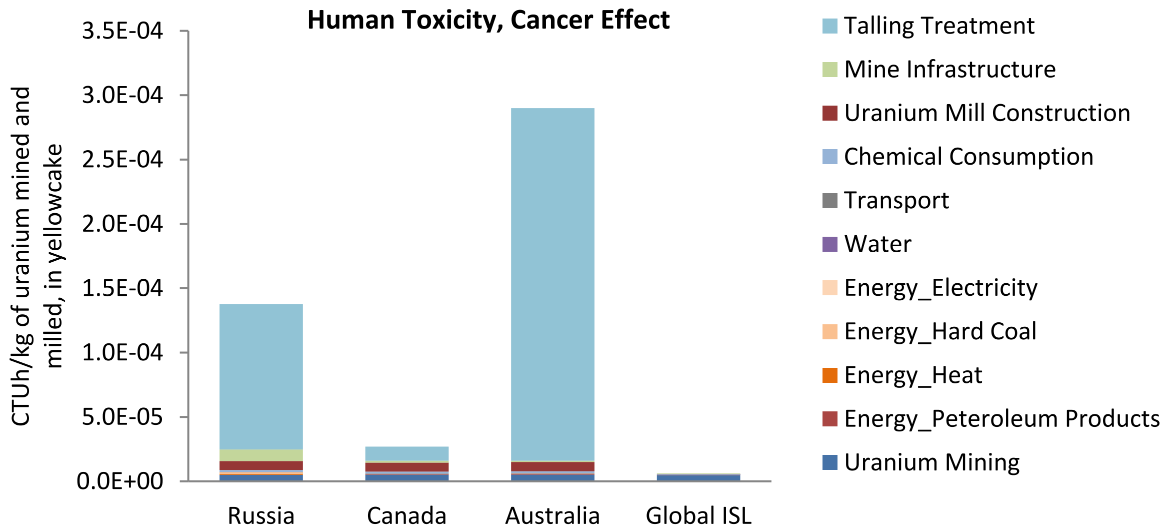
(Functional unit: 1 kg of uranium in yellowcake mined and milled)

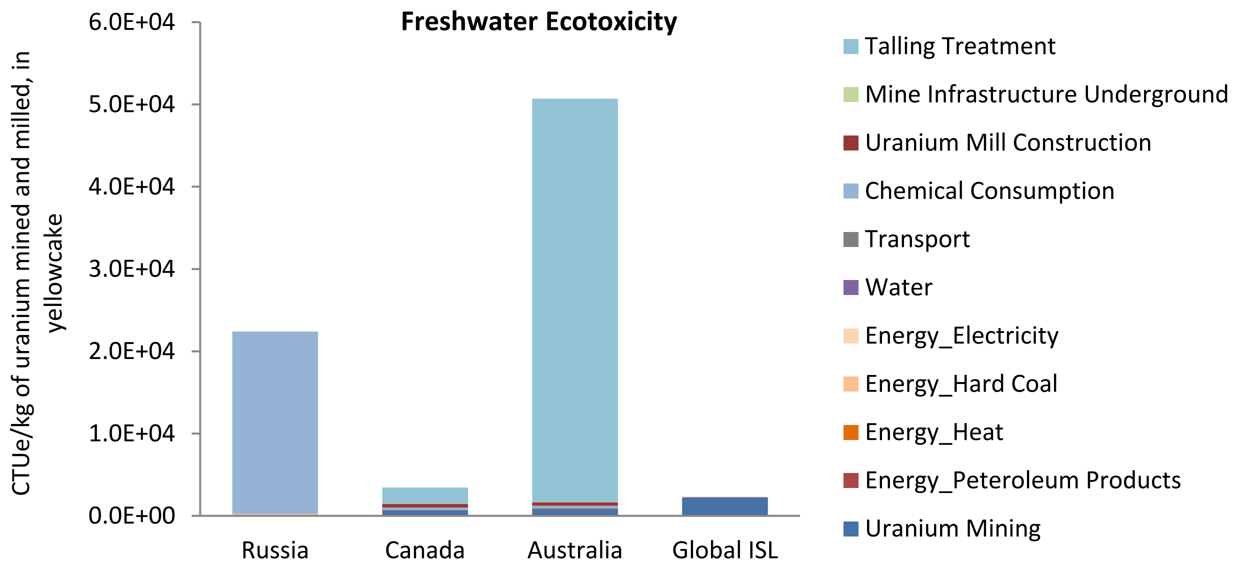


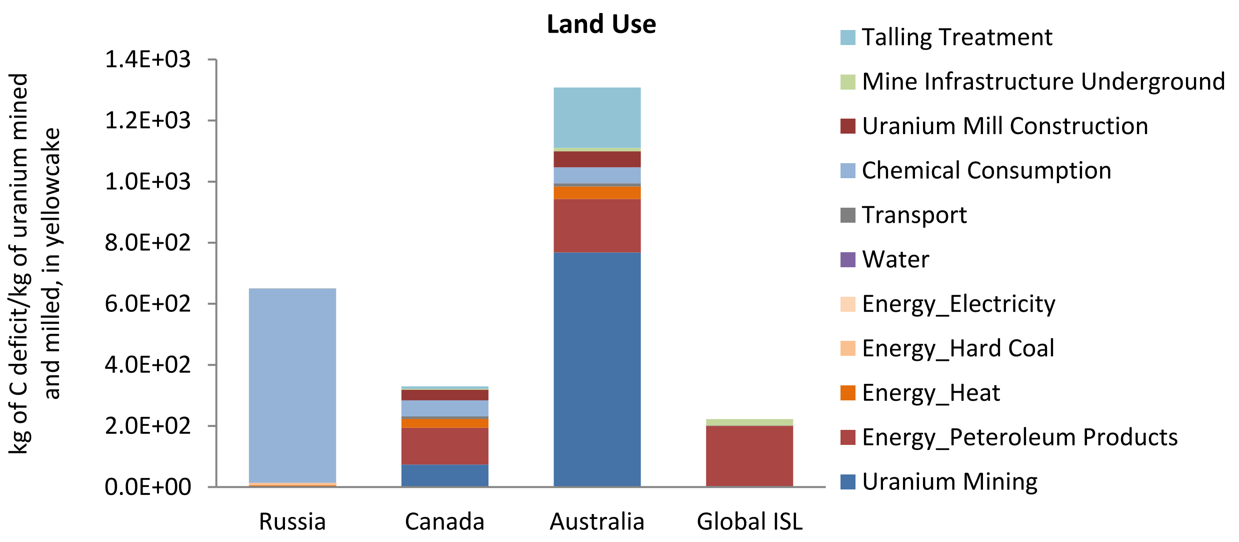

Ioninzing Radiation on Human Health
kBq U235 eq/kg of uranium mined and milled, in yellowcake
1.4E+05
1.2E+05
1.0E+05
8.0E+04
6.0E+04
4.0E+04
2.0E+04
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining

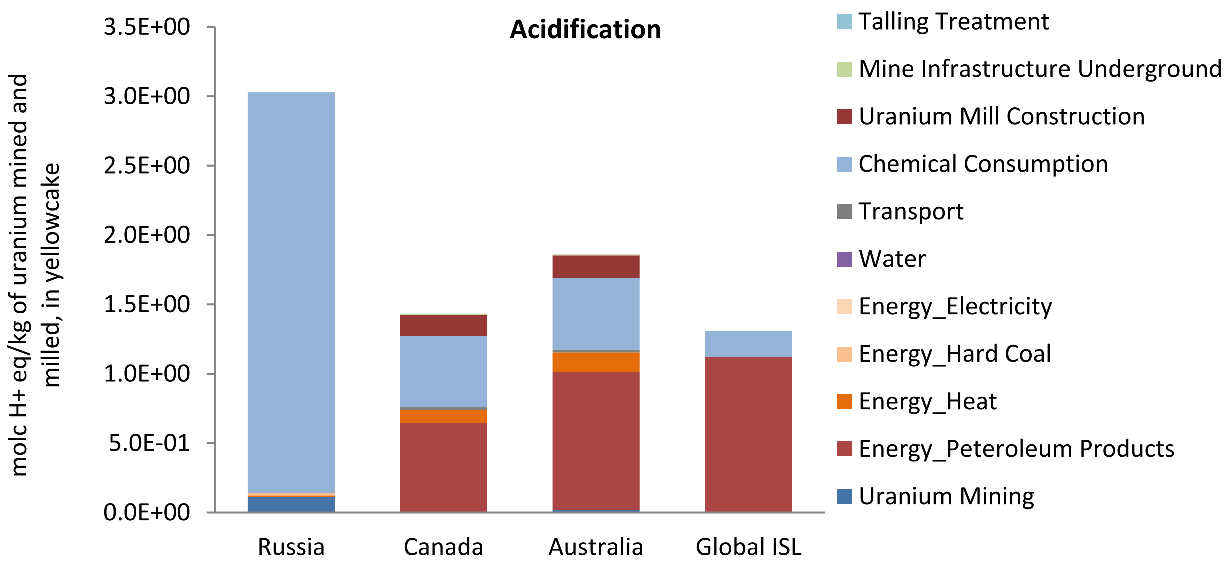

Particulate Matter
kg PM2.5 eq/kg of uranium mined and milled, in yellowcake
3.0E+00
2.5E+00
2.0E+00
1.5E+00
1.0E+00
5.0E-01
0.0E+00
-5.0E-01
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining


Human Toxicity, Non-cancer Effect
CTUh/kg of uranium mined and milled, in yellowcake
6.0E-03
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining


Human Toxicity, Cancer Effect
CTUh/kg of uranium mined and milled, in yellowcake
3.5E-04
3.0E-04
2.5E-04
2.0E-04
1.5E-04
1.0E-04
5.0E-05
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining


Freshwater Ecotoxicity
CTUe/kg of uranium mined and milled, in yellowcake
6.0E+04
5.0E+04
4.0E+04
3.0E+04
2.0E+04
1.0E+04
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining


Land Use
kg of C deficit/kg of uranium mined and milled, in yellowcake
1.4E+03
1.2E+03
1.0E+03
8.0E+02
6.0E+02
4.0E+02
2.0E+02
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining


Acidification
molc H+ eq/kg of uranium mined and milled, in yellowcake
3.5E+00
3.0E+00
2.5E+00
2.0E+00
1.5E+00
1.0E+00
5.0E-01
0.0E+00
Russia
Canada
Australia
Global ISL
Talling Treatment
Mine Infrastructure Underground
Uranium Mill Construction
Chemical Consumption
Transport
Water
Energy_Electricity
Energy_Hard Coal
Energy_Heat
Energy_Peteroleum Products
Uranium Mining

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