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Life cycle assessment of nuclear power in France: EDF case study

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Abstract. The French electricity mix is dominated by nuclear power, representing 69% of the power generation in 2021, and further development of nuclear power for electricity is expected. This study applied Life Cycle Assessment (LCA) to evaluate the potential environmental impact of nuclear power generated by EDF SA., the world's largest nuclear operator and electric utility company operating all the nuclear reactors in France. The study's main objective was to assess the potential environmental impacts of nuclear power, from raw material extraction to end-of-life, according to several indicators, while focusing on the climate change indicator. The total impact of nuclear power on climate change (3.7 gCO_2eq/kWh) is found to be in the lower range of LCA studies on nuclear power conducted so far. Mining and milling of uranium are the most contributing stages, while EDF's electricity generation is the second largest contributor. The key output of this LCA is the extensive data collected, resulting in a detailed LCA model covering the entire French nuclear fleet. Future studies should focus on (1) collecting more specific data on uranium mining and processing, as these are so far based on database data, and (2) addressing other LCA indicators, such as water use, land use, and ecotoxicity.

1 Introduction

The energy sector is an important driver of economic growth providing energy for industry, buildings, transport, agriculture, and fishing. Moreover, it has a key role in climate change mitigation, as energy is responsible for about three-quarters of global greenhouse gas emissions [1]. Power generation represents around 41% of the global CO_2 emissions due to energy combustion [2]. With the ambition of many countries to reach carbon neutrality at different time horizons, the energy sector will have to undergo major changes to reduce its emissions. Electrification will be at the heart of these changes, as electricity generation is faster to decarbonize. In 2021, 60% of global electricity came from fossil fuels (oil, gas and coal), 30% from renewables (hydro, solar, wind and biomass), and 10% from nuclear.

In the Net Zero by 2050 report published by IEA, the Net-Zero Emissions scenario describes how the energy demand and energy mix will need to evolve for the world to achieve net-zero emissions by 2050. In this scenario, global electricity generation doubles from 2020 to 2050, with almost 70% of electricity production coming from renewable energies, and 10% from nuclear, requiring a doubling of nuclear power capacity [1]. The share of electricity in final energy use should increase from 20% in 2020 to 50% in 2050.

The electricity mix in France is dominated by nuclear power; in 2021, 69% of electricity came from nuclear [3]. With a carbon intensity of 56.9 g CO_2eq./kWh, the French electricity mix has an impact on climate change 7 times lower than the European average [4]. It is nuclear power together with wind, solar and hydroelectric power that maintains the carbon intensity of the French electricity mix at such a low level. Carbon emissions from the energy sector are estimated to decrease with increasing electrification of the energy mix and an important decarbonization of electricity mix, according to the French low carbon strategy (*Stratégie française pour l'énergie et le climat,* Ministère de la transition énergétique, 2023) [5]. To achieve carbon neutrality in 2050, electricity must be at least 55% of the French energy mix. Further development of nuclear power for electricity, together with renewables, was considered as a valid solution in some of the scenarios proposed in the study on the evolution of the French electricity mix towards carbon neutrality by 2050 [6].

In the context of increasing environmental concerns, it is essential to assess the potential environmental impacts of the life cycle of nuclear power. Life Cycle Assessment (LCA) is one of the most comprehensive methods for quantifying the potential environmental impacts of a product or service, over its entire life cycle, from raw

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material extraction to end-of-life. According to ISO 14040 and 14044 standards [7,8], LCA is divided into four steps: (1) definition of the objective and scope (2) life cycle inventory (3) life cycle impact assessment and (4) interpretation.

LCA is a method that is increasingly used, particularly in the energy sector, to provide decision-making tool for technology development policies. However, there are still few multi-criteria LCA studies dedicated to nuclear energy and the variability of the results of existing studies remains significant. A multicriteria study on nuclear power in France was conducted by the CEA (French Alternative Energies and Atomic Energy Commission) based on 2010 data [9]. Similar LCA study assessing 7 environmental indicators was conducted for Switzerland [10]. LCA approach was applied to assess specific nuclear power plants in Sweden [11], in the UK [12] and Australia [13]. Existing review papers focus on GHG emissions over the life cycle of nuclear power and reveal significant variations of results [14–17]. The results range from 1.4 to 288 gCO_2e/kWh [16,17], with an average of 65 gCO_2e/kWh [17]. These discrepancies are often due to differences in the scope and assessment methods applied. Moreover, majority of studies is based on relatively old data from the 2000s or earlier. Thus, the importance of specific multicriterial studies based on recent data.

The study carried out in this paper is a process-based attributional LCA undertaken on the French nuclear fleet of EDF SA (*Electricité de France*), the French multinational electric utility company operating all the nuclear reactors in France, the second largest nuclear fleet in the world.

This paper is structured as follows. Chapter 2 presents the EDF nuclear sector in France and describes the nuclear fuel cycle. In Chapter 3, life cycle assessment is presented, together with goal and scope of the study; functional unit, system boundaries and environmental indicators are also described. Global results are presented in Chapter 4, followed by detailed results for climate, resource depletion and other indicators. Results on flow indicators for direct water consumption at nuclear power plant, and waste production, as well as a qualitative analysis for ionizing radiation impact are also presented. Sensitivity analysis is described in Chapter 4.6. In Chapter 5, the results on climate change are compared to other studies, this is followed by study limitations and suggestions for future research.

2 EDF nuclear sector in France

In 2019, EDF SA. produced 380 million MWh of nuclear electricity from 58 reactors (including the Fessenheim reactors, in operation in 2019 and no longer in service), spread over 19 locations. Out of 58 reactors, 34 have an electrical power of 900 MW, 20 of 1300 MW and 4 of 1450 MW. 22 of the 900 MW reactors are “moxed”, i.e., using both UOX (Uranium Oxide) fuel and MOX (Mixed Uranium Oxide and Plutonium) fuel.

The simplified scheme of the French nuclear fuel cycle is presented in Figure 1. Its main stages are detailed in the below sections.

Extraction and concentration (milling) of uranium ore

Several types of uranium mining techniques exist. This study considered: open-pit mining, underground mining (if uranium is too far below the surface for open-pit mining), and in situ leaching (ISL). ISL known also as solution mining allows recovering of uranium by dissolving it in the ground, and pumping the solution to the surface, where the uranium can be recovered. The uranium content of the extracted ore is often quite low and requires milling in several stages to separate uranium from other minerals.

Conversion, enrichment, and fuel production

Uranium extracted from mines and concentrated in the form of uranium oxide (U_3O_8) must be purified and enriched before being used as fuel in the reactors. Since enrichment requires uranium in gaseous form, it must be first transformed into UF_6 in conversion plants. The UF_6 obtained has a ^{235}U content of about 0.72%, which must be increased to between 3% and 5%, the required ^{235}U content of the French nuclear reactors. Uranium can be enriched using several technologies, such as gaseous diffusion, gas centrifugation, and laser separation [18]. The enrichment step aims at increasing the ^{235}U content of UF_6. In France, the current enrichment is based on centrifugation technology, which consumes far less electricity than the previously used gaseous diffusion facilities. This decrease in the electricity consumption could explain a part of the decreased amount of CO_2 released per kWh from nuclear generation in France, when compared to previous estimations [19].

Before being introduced into the reactors, the enriched UF_6 must be transformed into UO_2 (uranium oxide) and put into the form of fuel elements. The fuel elements consist of an assembly of 264 fuel rods supported by a structure called a skeleton. Fuel rods are made of fuel pellets, manufactured from pressed, UO_2 power, encased in zirconium alloy tubes.

MOX fuel follows the same manufacturing stages as UO_2 fuel but is produced from a mixture of UO_2 powder depleted in ^{235}U and PuO_2 powder from the processing of spent fuel.

Electricity production

The French electronuclear sector uses pressurized water reactors (PWR) with enriched uranium as fuel and ordinary water as moderator and coolant fluid.

The PWRs include three independent circuits:

- The primary circuit under high pressure (around 155 bar) extracts the heat generated by nuclear fission from the core and transfers it to the secondary circuit through heat exchangers (or steam generators).
- In the secondary circuit under lower pressure (around 70 bar), the water, heated by primary water in steam generators, vaporizes and then sets the turbogenerator in movement.

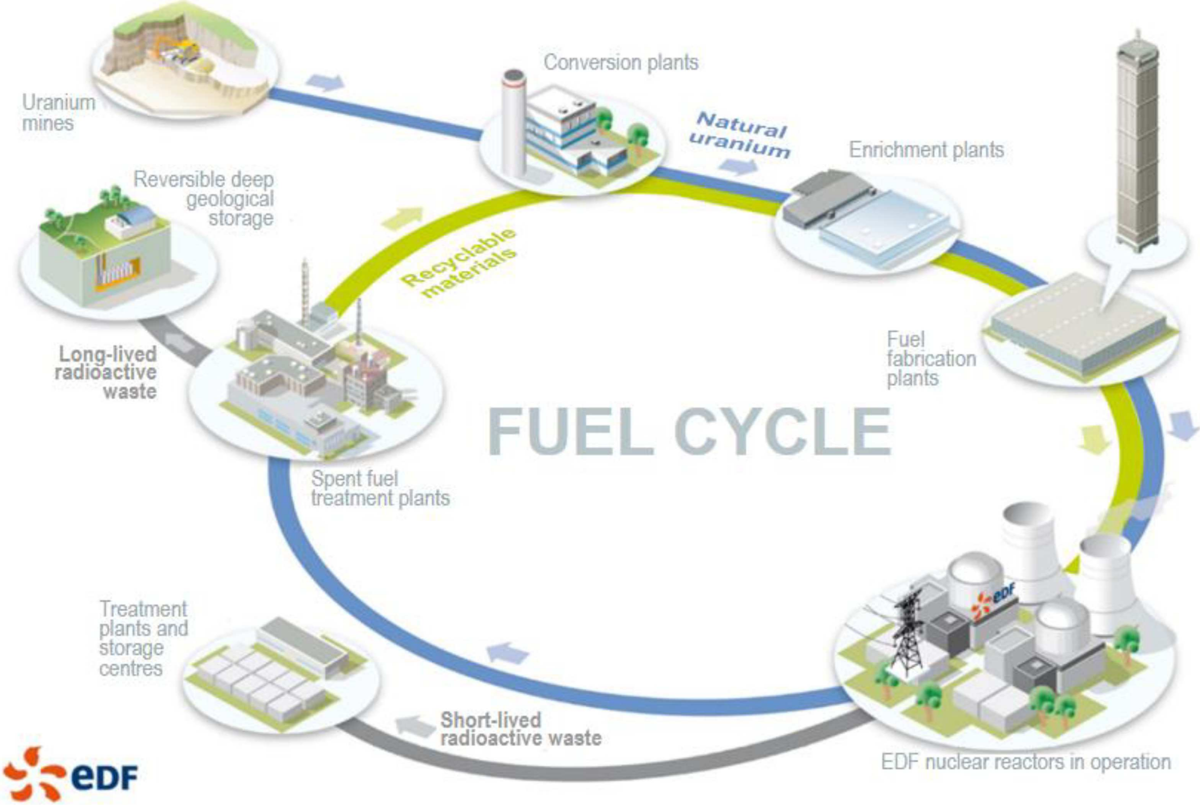

Fig. 1. Simplified description of the EDF SA electronuclear cycle (EDF SA source).

- The cooling circuit allows the condensation of circuit steam in contact with cold water from rivers or sea. The heated water can be directly discharged to river or sea or evaporated via a cooling tower.

A PWR allows to use of a part of the thermal energy released during the nuclear fission of fissile atoms ^{235}U and ^{239}Pu to heat water and produce steam, which activates a turbogenerator set, generating electricity. The fission reaction generates various fission products replacing fissile atoms in the fuel assemblies. The assemblies must therefore be renewed to compensate for the progressive fuel exhaustion. The spent fuel assemblies are stored for at least one year in a pool filled with water. It allows to evacuate of the residual heat released from the assemblies and guarantees protection against radiation.

The liquid and gaseous radioactive effluents are collected and treated to absorb the essential part of their radioactivity, and then sent to storage reservoirs where they are kept until their radioactivity decreases to the levels that allow their safe discharge to the environment.

The construction of reactors (construction site, mechanical equipment, pipes, ventilation, electric equipment and cables, and control equipment) has required important quantities of reinforcement steel, concrete but also formwork, cables, pipes and supports dedicated to the different reactor equipment.

The dismantling of nuclear power plants includes three phases:

- The final shutdown (unloading of fuel, draining of circuits and final shutdown); 99.9% of the radioactivity present on the site is then eliminated.
- Dismantling of the buildings adjacent to the reactor building itself.
- Dismantling the building, with optimization of waste management.

Treatment of the spent fuel

The treatment of the spent fuel consists in separating recyclable and recoverable materials, representing 96% of the spent fuel, from the final waste, which represents only 4% of the fuel.

Disposal facilities for radioactive waste

Radioactive waste classification in France is primarily based on two parameters, which are important when determining the appropriate management method: the activity level and the radioactive half-life of the radionuclides contained in the waste.

A distinction is made between the following waste activity levels:

- very low-level waste (VLLW), with an activity level less than 100 becquerels per gram;

- low-level waste (LLW), with an activity level between a few hundred becquerels per gram and one million becquerels per gram;
- intermediate-level waste (ILW), with an activity level from around one million to one billion becquerels per gram;
- high-level waste (HLW), with an activity level around several billion becquerels per gram.

Waste is classified according to radioactive half-life as follows:

- very short-lived waste (VSLW), which contains radionuclides with a half-life of less than 100 days;
- short-lived (SL) waste, whose radioactivity comes mainly from radionuclides with a half-life of less than or equal to 31 years;
- long-lived (LL) waste, which contains a significant quantity of radionuclides with a half-life of more than 31 years.

The nuclear waste generated by the EDF nuclear is managed by three different methods, thus this study considers three kinds of nuclear waste:

- VLLW, very low-level waste ("TFA"), produced during power plant operation, clean-up and dismantling operation (disposed of a surface facility, Morvilliers site)
- LILWSL, intermediate and low-level short-lived waste ("FMA-VC"), produced during operation, maintenance, or dismantling waste (disposed of a surface facility, Soulaines site)
- HLW&ILW-LL, high level and intermediate level long-lived waste ("HA/MA-VL") brings together two types of waste which have the same outlet (CIGEO project), but of a different nature : HLW, with high thermal density, conditioned in stainless steel containers (CSD-V) come from the processing of spent fuel, while ILW-LL comes from the processing of fuel (CSD-C), from reactor operation (maintenance) and deconstruction

3 Method

3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is the reference method for evaluating the potential impacts of a system (product, service, process, channel) on the environment (multi-criteria approach). It is based on the inventory of material and energy flows for the different life cycle stages, from the extraction of raw materials to the management of waste. This is known as a multi-stage *cradle to grave* approach. The multi-stage and multi-criteria aspect of the methodology is a key element to avoid pollution transfers from one stage to another or from one environmental aspect to another.

LCA is recognized as the main method for environmental assessment and is governed by the ISO 14040 and ISO 14044 standards [7,8]. LCA can be divided into the following steps:

1. The definition of the objectives and scope of the study, which clarifies the functions of the studied system. A functional unit is then defined, and the system boundaries are determined to identify the life cycle stages to be considered in the study.
2. The life cycle inventory of the system, which identifies the material and energy flows for each of the life cycle stages.
3. Environmental impacts assessment, where all the inventoried flows are translated into "potential impact indicators", quantifying the potential contribution of the system to major environmental problems (greenhouse effect, acidification, etc.).
4. Interpretation of the results, where the conclusions are drawn, and limits are reminded. This step is iterative with the previous ones, to ensure that the results obtained meet the objectives of the study.

3.2 Goal and scope definition

This is an attributional LCA focused on the current EDF nuclear fleet in France excluding any modelling of future scenarios. The general objective of this study is to broaden the scope of knowledge on the environmental impact of nuclear power generation over its entire life cycle.

The specific objectives of this study are to:

- Generate a detailed life cycle model of kWh produced by the EDF nuclear fleet.
- Evaluate the potential environmental impact of nuclear power generated by EDF, based on LCA indicators and flow indicators, with a focus on climate change.
- Produce a sound and scientific base for further research by encouraging collaboration between the actors of the nuclear sector and propose recommendations for further development.

3.2.1 Function and functional unit

Life cycle assessment is based on the study of the function of a system and defines a "functional unit" which represents a quantification of the function of the system studied (performance and duration of operation). For this study, the functional unit is to: "*Produce one kWh of electricity from the French EDF nuclear fleet*". The 1 kWh of nuclear power generated is fed into the grid. In principle, 2019 data were used (especially for the electricity production stage), and when not available, the most recent data were applied.

3.2.2 System boundaries

The definition of the system boundaries allows the identification of all relevant activities (life cycle stages, processes, flows) that are considered in the LCA and that are consistent with the purpose of the study. In this study, the following main life cycle stages were considered:

- *The extraction of the uranium ore and its milling ("Mines")*: includes all energy consumption of the

mines, as well as the materials and energy for separating uranium from the other ore constituents; mining waste and transportation from the mines to the various processing centers are also considered.
- *The conversion, enrichment, and generation of the fuel ("Fuel")*: includes reagents and energy consumptions, losses of uranium within the various sites, as well as transportation between sites.
- *The electricity production (construction, operation, and dismantling stages of the nuclear power plants) ("Electricity production")*: includes energy and materials for the construction of reactors, operation and heavy maintenance, as well as dismantling and waste.
- *Spent fuel treatment ("Spent fuel treatment")*: includes energy use and reagent consumption during the processing operation, as well as waste production.
- *The disposal facilities for the radioactive waste ("Waste storage")*: includes energy use, storage center infrastructure, and transportation of various types of waste (VLLW, LILW-SL, HLW & ILW-LL) to their disposal facilities.

The construction of the facilities required through the life cycle (mines infrastructures, plants for the production of the fuel and spent fuel treatment), is also included. The transmission of electricity was excluded from the scope, as it is outside of the direct control of EDF. Finally, the construction of new reactors (EPR) was excluded, as well as the flows that are related to administrative services and transport of employees.

3.3 Life cycle inventory

Different sources of data were used. Primary data specific to the EDF nuclear fleet were collected by EDF for year 2019 and concerned the electricity production stage (construction, operation, and dismantling). For the remaining life cycle stages, they are outside of EDF control, and therefore, the data and hypothesis applied were mainly based on the ecoinvent database 3.6 [20]. Two complementary sources of primary data were also used:

- Orano/PNGMDR report [21], assembling the most up-to-date data for the French electronuclear cycle, which however did not undergo a critical review and is not representative of EDF suppliers.
- EDF in-house expertise; internal experts for each life cycle stage were consulted and the ecoinvent data updated, if necessary, in full transparency.

Hypothesis concerning EDF suppliers of uranium, largely common to Euratom suppliers, were based on data published annually by the Euratom Supply Agency of the European Commission [22].

Secondary data for the background processes, such as environmental balance of concrete, steel, electricity, and transport, were based on the ecoinvent database 3.6. [20].

Table 1 shows the main life cycle inventory data of EDF nuclear kWh.

3.4 Environmental evaluation

The potential impact indicators of the International Life Cycle Data system (ILCD) were used in this study [23]. Results were presented for 10 indicators, each ranked I or II for their level of robustness (Tab. 2). Robustness defines the degree of recognition and soundness of the model behind each indicator by LCA experts.

Four ILCD indicators were not considered in this study: water consumption, land use, human toxicity and freshwater ecotoxicity. This is mainly because of their low robustness (III for water consumption and land use, and II/III for human toxicity and freshwater ecotoxicity). For land use [24], the integration of scientifically sound indicator is still at research level. For both human toxicity and freshwater ecotoxicity based on USEtox model [25], there are important uncertainties associated with the model.

Two quantitative flow analyses were added for water consumption and waste production. Water use at nuclear power plant was identified as an important issue [21]. Thus, the water consumption was assessed using direct measurements of withdrawals and discharges of water at power plant level. Waste treatment and related energy consumption and emissions are included in the study, and its potential impact assessed through ILCD indicators. Additionally, the quantity of waste produced, both conventional and radioactive was used as a flow indicator. Finally, a qualitative analysis was conducted for ionizing radiations, based on the monitoring of radionuclide emissions, to complement the ILCD LCA indicator.

Four sensitivity analyses were conducted in this study, all on climate change indicator. First, more up-to-date characterization factors for climate change were tested. Also, diesel consumption at mining & milling, nuclear plant operating lifetime and total electricity production were used as variables in three separate analyses.

The LCA modelling including all the data and assumptions, was conducted in LCA software Simapro 8.5.

4 Results

4.1 General results

Table 3 and Figure 2 present the life cycle assessment results of EDF nuclear power generation in France expressed per 1 kWh. Mining is the main contributing stage for all indicators, except ionizing radiations, for which the electricity production and spent fuel treatment have the highest contribution. These two stages have a significant contribution to all indicators, excluding resource depletion, as this indicator is mainly driven by mining. Waste storage is the least contributing stage for all indicators. The detailed analysis is presented further focusing on each indicator separately.

Table 4 presents an extract of the LCA inventory including the flows identified as prevailing for some indicators.

Table 1. Life cycle inventory of the EDF nuclear kWh. (EDF/DCN = EDF Nuclear Fuel Division).

Stage	Sub-stage	Data		Unit	Value	Source/Comments
Mines	Extraction – Processing	Geographical distribution of mines	Australia	%	16%	Euratom data
			Open-pit mines	*%*	*24%*	EDF/DCN
			Underground mines	*%*	*50%*	EDF/DCN
			ISL mines	*%*	*26%*	EDF/DCN
			Canada	%	21%	Euratom data
			Underground mines	*%*	*100%*	EDF/DCN
			Namibia	%	10%	Euratom data
			Open-pit mines	*%*	*100%*	EDF/DCN
			Niger	%	17%	Euratom data
			Open-pit mines	*%*	*63%*	EDF/DCN
			Underground mines	*%*	*37%*	EDF/DCN
			Russia	%	18%	Euratom data
			Underground mines	*%*	*47%*	EDF/DCN
			ISL mines	*%*	*53%*	EDF/DCN
			Kazakhstan	%	18%	Euratom data
			ISL mines	*%*	*100%*	EDF/DCN
		Electricity consumption	Open-pit and underground mine	kWh/kg U3O8	35	EDF/DCN
			ISL mine	kWh/kg U3O8	40	EDF/DCN
		Diesel consumption	Open-pit mine	m3/kgU3O8	0,015	EDF/DCN
			Underground mine	m3/kgU3O8	0,004	EDF/DCN
			ISL mine	m3/kgU3O8	0,002	EDF/DCN
		Mining waste		m3/kgU3O8	0,25	ecoinvent data
Fuel	Conversion	Conversion market distribution	Cameco (Canada)	%	51	Euratom data
			Orano (France)	%	27	Euratom data
			TENEX/Rosatom (Russia)	%	22	Euratom data
	Enrichment	Enrichment market distribution	Orano (France)	%	35	Euratom data
			Urenco (Germany)	%	11,67	Euratom data
			Urenco (Netherlands	%	11,67	Euratom data
			Urenco (UK)	%	11,67	Euratom data
			TENEX/Rosatom (Russia)	%	30	Euratom data
		Enrichment content	4% content 4%	kgU/UTS*	1,23	For 1300-MW and 1400-MW reactors
			4,2% content	kgU/UTS*	1,21	For "Cyclades" 900-MW reactors
			3,7% content	kgU/UTS*	1,27	For "Garance" 900-MW reactors and "moxed" 900-MW reactors
		Electricity consumption		kWh/UTS	35,5	EDF
	Fuel production	UOX and MOX fuel	Uranium losses	%	0,58	EDF/DCN
Electricity production	Construction	Amount of concrete	Reactors of a 900-MW unit electric power	Tons	199 108	EDF
			Reactors of a 1350-MW unit electric power	Tons	384 714	EDF
			Reactors of a 1450-MW unit electric power	Tons	393 481	EDF
		Amount of reinforcing steel	Reactors of a 900-MW unit electric power	Tons	16 140	EDF
			Reactors of a 1350-MW unit electric power	Tons	32 280	EDF
			Reactors of a 1450-MW unit electric power	Tons	33 042	EDF
		Amount of steel equipment	Reactors of a 900-MW unit electric power	Tons	17 194,5	EDF
			Reactors of a 1350-MW unit electric power	Tons	25 620	EDF
			Reactors of a 1450-MW unit electric power	Tons	25 104	EDF
	Operation	Operating time		Years	40	EDF
		SF6 emissions		kg/year	2178	EDF
Spent fuel treatment	Spent fuel treatment	Energy consumptions, reagents consumption, waste production				ecoinvent data updated with information from [21].
Waste storage	Waste storage	Waste transport, treatment and storage of all types of waste (VLLW, LILW-SL, HLW & ILW-LL)				ecoinvent data updated with information from EDF

Table 2. Environmental indicators selected for this study.

Indicator	Unit	Robustness
Climate change	kg eq. CO_2	Level I
Ozone depletion	kg CFC-11 eq.	Level I
Particulate matter/respiratory inorganics	kg PM2.5 eq.	Level I
Ionizing radiation, human health	kg U235 eq.	Level II
Photochemical ozone formation	kg NMVOC eq.	Level II
Acidification	mol H+ eq.	Level II
Eutrophication, terrestrial	mol N eq.	Level II
Eutrophication, aquatic, freshwater	kg P eq.	Level II
Eutrophication, aquatic, marine	kg N eq.	Level II
Resource depletion	kg Sb.eq.	Level II

Table 3. Life cycle assessment results of the nuclear kWh of EDF SA. on the selected indicators.

Indicators	Unit (/kWh)	Total	Mines	Conversion	Enrichment	Fuel production	Electricity Production	Spent fuel treatment	Waste storage
Climate change	$kgCO_2eq$	**3.67E–03**	1.34E–03	2.53E–04	4.36E–04	7.09E–05	1.02E–03	4.76E–04	7.57E–05
Ozone depletion	kg CFC-11 eq	**4.73E–10**	1.27E–10	2.73E–11	5.89E–11	1.62E–11	1.09E–10	1.28E–10	7.08E–12
Particulate matter	kg PM2.5 eq	**3.22E–06**	1.39E–06	1.30E–07	3.00E–07	5.34E–08	8.77E–07	4.02E–07	6.66E–08
Ionizing radiation	kBq U235 eq	**6.81E–01**	1.32E–02	7.32E–05	7.51E–03	1.94E–05	2.50E–01	4.10E–01	7.60E–06
Photochemical ozone	kg NMVOC eq	**2.07E–05**	1.07E–05	1.58E–06	1.64E–06	3.32E–07	4.70E–06	1.37E–06	2.89E–07
Acidification	molc H+ eq	**3.45E–05**	9.38E–06	4.41E–07	2.41E–06	1.98E–06	1.69E–05	2.71E–06	6.06E–07
Eutrophication, terrestrial	molc N eq	**7.12E–05**	3.63E–05	5.84E–06	6.00E–06	1.24E–06	1.57E–05	5.17E–06	9.37E–07
Eutrophication, freshwater	kg P eq	**1.90E–07**	7.70E–08	6.37E–09	2.69E–08	3.35E–09	5.23E–08	1.87E–08	5.26E–09
Eutrophication, marine	kg N eq	**1.47E–05**	1.04E–05	4.58E–07	5.37E–07	2.34E–07	1.38E–06	1.63E–06	7.79E–08
Resource depletion	kg Sb eq	**4.81E–06**	4.64E–06	7.77E–08	1.08E–08	1.52E–09	5.20E–08	3.26E–08	3.91E–09

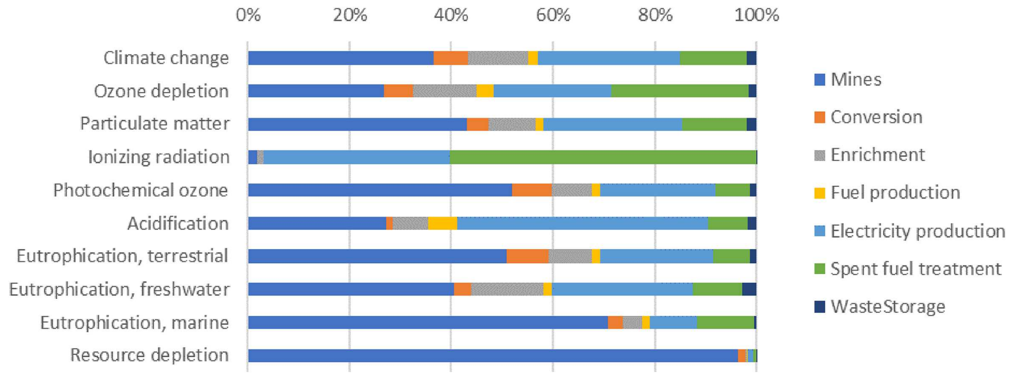

Fig. 2. Contribution analysis on the life cycle assessment results of the nuclear kWh of EDF SA.

4.2 Climate change

EDF nuclear power generation in France has an impact of 3.7 gCO_2eq/kWh. CO_2 emissions bear 85% of that impact, CH_4, N_2O and SF_6 represent respectively 5%, 4% and 4% of the impact. The N_2O of the conversion stage proceeds from the consumption of nitric acid (1.4 $kgHNO_3/kg$ UF_6). The SF_6 emissions are mainly occurring during the production stage (2178 kg/year) (Fig. 3).

The back-end life cycle stages have the highest impact on climate change (57%), with the highest contribution coming from mines (36%). The main contributors towards the back-end stages are:

- mining and uranium milling: diesel (12% of the indicator) and electricity consumption (12% of the indicator)

Table 4. Life cycle inventory of the nuclear kWh of EDF SA (extract).

		Unit (kWh)	Results	% of the mentioned indicator
Emissions	CO_2	g	3.1	85% climate change
	Halon1301	ng	15.4	39% ozone layer depletion
	PM2.5	mg	3.05	63% particulate matter
	Sulfur oxides and sulfur dioxide	mg	16.2	63% acidification
	Nitrogen oxides and nitrogen dioxide	mg	14.9	72% photochemical ozone, 89% terrestrial eutrophication
	Phosphate in water	μ g	555	96% freshwater eutrophication
	Nitrate in water	mg	32.9	51% marine water eutrophication
	Carbon 14 (air)	Bq	66.5	98% ionizing radiations
Inputs	Oil	g	0.3	
	Coal	g	0.6	
	Lignite	mg	0.3	
	Natural gas	m3	0.0004	
	Uranium	mg	21.9	
Waste	Non-Dangerous Waste	g	0.1	
	Dangerous Waste	g	0.03	
	VLLW waste	g	0.03	
	LILW-SL waste	g	0.1	
	HLW & ILW-LL waste	g	0.002	

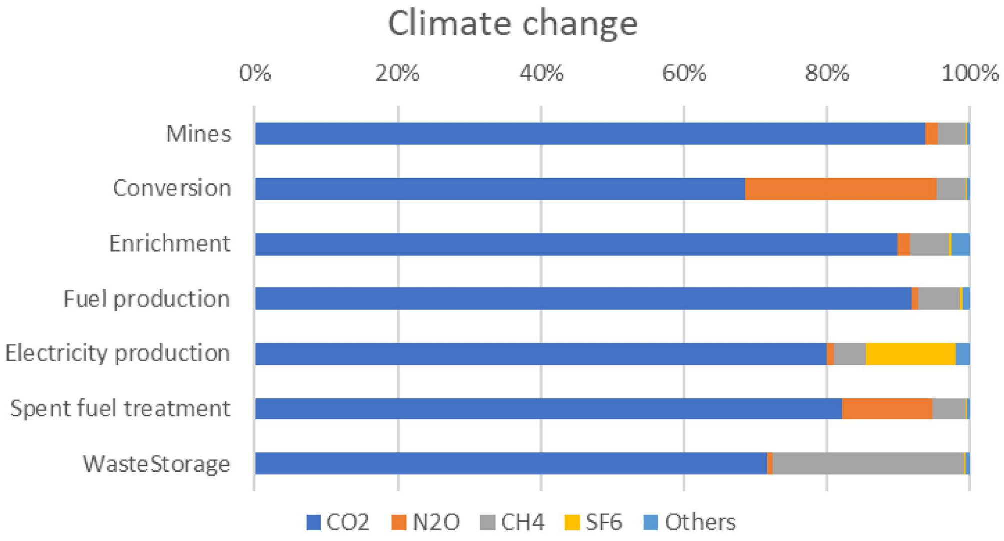

Fig. 3. Climate change indicator, flow contribution analysis per stage.

- conversion: consumption of nitric acid (3% of the indicator)
- enrichment: electricity consumption (5% of the indicator).

The electricity production at EDF (construction, operation and dismantling) represents 28% of the climate change indicator, with construction representing the highest contribution. The main contributors to the indicator are cement (6%), unalloyed steel (3%) and concrete steel (2%). The operation represents 9% linked mainly to the SF6 emissions (4% of the impact, 2 178 kg per year in 2019), and diesel consumption (2% of the impact, 8800 m3/year). The dismantling represents a marginal impact (3%). Maintenance, included in the operation, is also marginal in the balance (1%). The two most contributing consumptions for maintenance are inconel (containing nickel) and titanium, mainly due to the replacement of steam generators and capacitors.

Table 5. Resource depletion indicator - mineral substances (Uranium excluded).

Substance	Kg Sb eq/kWh	% of the indicator (uranium excluded)	Value (kg)	Origin
Gold	2,2E–07	54%	6,10E–09	85% sulfuric acid for mines (linked to modelling choice)
Fluorspar	6,8E–08	17%	2,60E–05	100% hexafluoride (conversion: 0,6 kg/kg UF6)
Nickel	4,0E–08	10%	1,00E–05	Steel low alloyed: construction (31%), spent fuel treatment (39%, of which zircaloy 24%)
Silver	2,4E–08	6%	2,80E–09	84% sulfuric acid for mines
Copper	1,75E–08	4%	7,00E–06	46% plant construction
Zinc	9,8E–09	2%	2,70E–06	85% sulfuric acid for mines
Lead	9,0E–09	2%	6,00E–07	85% sulfuric acid for mines
Zirconium	7,5E–09	2%	4,50E–07	44% titanium for compressor (reactors close to sea)
Others	1,0E–08	3%		

Treatment of the spent fuel contributes to a lesser extent (13%) and its impact is linked to heat (fuel boilers) and electricity consumption. Storage of waste at end-of-life is negligible.

4.3 Resource depletion

Resource depletion indicator is dominated (91%) by the mining of uranium (remember that the ILCD indicator takes uranium into account). Direct consumption of uranium by the electronuclear cycle represents 88% of the total uranium consumption (21.9 mg/kWh), the remaining 12% comes from uranium used for electricity generated outside France and consumed at various life cycle stages. Out of 9% of contribution beyond uranium, over half of it is linked to gold, other mineral resources contribute to much smaller extent (Tab. 5 excluding uranium). For the energy resources, the result for the total life cycle is dominated by use of coal, followed by natural gas and petrol, used at various life cycle stages of nuclear power (Tab. 6). The quantity of fossil fuels, such as petrol, coal and natural gas, used seems much higher in terms of mg/kWh than consumption of uranium. This is because the energy content of uranium is much higher than other energy resources listed.

Table 6. Energy resources consumptions.

Flows (consumptions)	
Petrol	323 mg/kWh
Coal	612 mg/kWh
Lignite	264 mg/kWh
Natural gas	380 cm3/kWh
Uranium	21.9 mg/kWh

4.4 Other ILCD indicators

4.4.1 Ozone depletion

The result on ozone depletion is driven by halon-1301, CFC-114, halon-1211, and CFC-10 emissions, in decreasing order. The most contributing substance, halon-1301, represents 39%, most of which from fuel consumption in the mines. Emissions of CFC-114 (37%) are most likely over-estimated, as the model uses obsolete data from the background ecoinvent inventory of fuel enrichment in the United States for the ecoinvent electricity datasets. In these data, the enrichment is conducted by gaseous diffusion with high emissions of CFC-114 (used as a refrigerant gas), however, this enrichment technology is no longer commercially available. The impact of CFC-114 on ozone depletion is therefore overestimated because this emission could not be corrected in all background process.

4.4.2 Particulate matter

For particulate matter, the PM2.5 (fine particles of less than 2.5 μm of diameter) represent 64% of the indicator, followed by SOx (32%) and NOx (3%). SOx and NOx are precursors of particulate matter: a significant part of these emissions will transform into particles in the air. The key contributors to the emissions of PM2.5 and SOx are diesel combustion (10% of the indicator) and sulfuric acid production (also 10%) during mining of uranium.

4.4.3 Photochemical ozone formation

NOx emissions into the air represent 72% of photochemical ozone formation. The key contributor to the emissions of NOx and NMVOC is the combustion of diesel during the mining process (17%).

4.4.4 Acidification

Acidification indicator is linked to SOx emissions (63%) and NOx emissions (32%). The production of sulfuric acid used during mining represents 17% of the indicator.

4.4.5 Terrestrial eutrophication

NOx emissions into the air are contributing the most (89%) to the terrestrial eutrophication, followed by ammonia emissions into the air (11%). The use of diesel for generating electricity in the mines is the main contributor (19%), relative to NOx emissions.

4.4.6 Freshwater eutrophication

The result on freshwater eutrophication is dominated by the phosphate emissions into water (96%), followed by the phosphorus emissions into water. Phosphate emissions into water are mainly linked to electricity consumption over the life cycle, especially in countries where the electricity mix is particularly carbon-intensive. Phosphorus emissions into water are mainly coming from the fuel production stage, and are linked to the consumption of zirconium.

4.4.7 Marine eutrophication

The emissions of nitrate into water contribute the most towards marine eutrophication (51%), followed by NOx emissions into the air, and ammonia emissions into water. Nitrate emissions are mainly due to ISL mining operations (80% of nitrate emissions).

4.4.8 Ionizing radiations

Ionizing radiations are dominated by carbon 14 emissions into the air (98%) related to the treatment of spent fuel (60%) and the electricity production at EDF (37%). Radon emissions during mining are negligible (less than 0.01%). To strengthen the analysis, LCA results are enhanced by qualitative analysis based on the monitoring of direct emissions, in particular of carbon 14.

4.5 Additional analysis on waste, water, and ionizing radiations

4.5.1 Waste and water

Some of the environmental indicators selected for this study remain incomplete and do not include all environmental issues related to the production of nuclear electricity. In addition to the LCIA results, other assessments on conventional waste, radioactive waste, and water consumptions, were included, based on data provided by EDF.

Conventional waste. There are two types of conventional waste in France: hazardous waste and non-hazardous waste. Direct production of hazardous and non-hazardous waste was accounted for along the entire life cycle (Tab. 7). The indirect conventional waste could not be included, resulting in an underestimation of at least 16%, based on the ratio between direct and total consumption of uranium (equal to 0.88). This assessment is only a first identification of the key contributors to waste production along the life cycle.

Table 7. Conventional waste quantities per nuclear kWh.

Waste type	kg/kWh	Prevailing stages
Non-hazardous waste	1.2E–4	Operation 88%
Hazardous waste	2.9 E–5	Operation 72%

Radioactive waste. This study considers various types of radioactive waste: VLLW, LILW-SL, HLW & ILW-LL, as described in the system boundaries (section 3.2.2). The direct production of radioactive waste through the life cycle was assessed (Tab. 8). Indirect radioactive wastes could not be included in this evaluation, resulting in an underestimation of at least 16%, based on the ratio between direct and total consumption of uranium (equal to 0.88). Based on the results, dismantling seems to be a key stage in the production of radioactive waste.

Water consumption. The water use indicator from ILCD was not retained for this study, as it is categorized with a robustness level of III. Instead, direct water withdrawals and discharges from EDF nuclear power plants were examined, as these are expected to account for the vast majority of water consumption over the life cycle of nuclear power [9]. Water is required by nuclear power plants to produce the steam driving the turbine, cool down the installations, supply safety reserves and firefighting circuits, and supply sanitary facilities and employee catering equipment. Water consumption for cooling the reactor is indicated in Table 9. An additional 0.03 L/kWh (freshwater) is required for industrial use and 0.003 L/kWh (tap water) for domestic use.

4.5.2 Ionizing radiations: monitoring of radionuclide emissions

The ionizing radiation ILCD indicator is not linked to the concept of absorbed dose, which is an essential measure of radioactivity. The exposure limits are set at national level to control the radiation level, so the public exposure remains as low as possible. To enhance the LCIA analysis, additional information is provided here based on the monitoring of radionuclide emissions at spent fuel treatment stage and operation stage.

Carbon 14 emissions during treatment of spent fuel. At this stage, a part of the carbon 14 is emitted in gaseous form at 100 m above the ground level, to promote dispersion and reduce the impact on the environment. The radioactivity that results from these emissions is permanently monitored. Measures made around the site are in the order of 0.03–0.1 Bq/m3 for carbon 14, below the

Table 8. Radioactive waste quantities per nuclear kWh.

Radioactive waste type	kg/kWh	Prevailing stages
VLLW	1.2E–4	Dismantling 59%
LILW-SL	2.9 E–5	Dismantling 53%
HLW & ILW-LL	1.6 E–6	Dismantling 50%, spent fuel treatment 50%

Table 9. Direct water consumption of the nuclear power plants per kWh.

Reactor type	Number of reactors	Production share	Water withdrawal	Water release	Water consumption – fleet average
		(%)	(L/kWh)	(%)	(L/kWh)
Once-through cooling system, ocean	18	28%	182	100%	1.3
Once-through cooling system, river	12	20%	169	99.8%	
Cooling tower system, river	28	52%	10	77%	

monthly average limit of 1 Bq/m3 fixed in the legislation by the French nuclear safety agency (*Autorité de Sûreté Nucléaire* (ASN), [26]). Orano, the treatment site operator, also performs measures of carbon 14 and other radionuclides in representative samples from the terrestrial and aquatic compartments (in plants, soil, milk, vegetables, fish, shellfish, etc.). In its 2020 report [27], Orano reports the dosimetric impact of discharges at La Hague site, on the population groups likely to be the most exposed, to be equivalent *"to less than 0,5% of the average exposure of the French population due to natural radioactivity. The IRSN (Radioprotection and Nuclear Safety Institute), in its report on the 2018–2020 French environment radiological state, considers carbon 14 as a secondary contributor to the total dose linked to the radioactive discharges of the La Hague Orano site, the latter contributing to 16% in the case of a representative scenario of an average food diet of a population living in North-Cotentin"*.

Radionuclide emissions at nuclear power plant operation stage. Nuclear power plants (NPPs) release radioactive effluents in the environment. These radionuclides are emitted in the atmosphere, rivers, or sea water after radioactivity level control. The ASN defines, for each NPP, specific release limits and modalities, to guarantee that under normal operation conditions the public exposure remains lower than 1 mSv/year, in compliance with article R1333-11 of the Public Health Code [28]. As shown by IRSN, the doses liable to be received by the population living around French NPPs are very low [29]. A person living around an NPP would receive, all exposure ways combined, a dose in the order of 1 μSv/year, i.e. 1/1000 of the audience exposure limit (1000 μSv/year) set in article R1333-11 of the Public Health Code.

4.6 Sensitivity analysis

Characterization method for the climate change indicator. For climate change, as the ILCD is based on IPCC 2007 [30]. The updated characterization factor from IPCC 2013 [31] were tested, and the resulted is the same (3.7 gCO_2eq/kWh). The LCIA methods do not include the most recent SF6 global warming potential; 25 200 kgCO_2eq/ kg SF6 in the last IPCC 2022 report [32] against 22 800 and 23 500 for IPCC 2007 and IPCC 2013, respectively. However, even when considering the most up-to-date values, there is no impact on the results for the climate change indicator.

Influence of the diesel consumption at mining/milling stage on the climate change indicator. Diesel consumption for the mining process is contributing significantly to the potential impacts of EDF nuclear power life cycle. Based on EDF expert opinion, a sensitivity analysis was performed to evaluate the influence of lower and higher values of diesel consumption for mining on the climate change indicators results (Tab. 10). The difference in result was small, with results varying from 3.5 to 3.95 gCO_2eq/kWh against 3.7 gCO_2eq/kWh in this study, so less than 13%. It is worth noting that the machinery needed to strip the rocks, as well as the trucks required for evacuation, are both responsible for the higher diesel consumption of the open-pit mines.

Influence of operating lifetime on the climate change indicator. The default operating lifetime of NPPs considered in this study is 40 years. Extending the lifetime to 60 years would reduce the climate change indicator by 8% (3.4 gCO_2eq/kWh). The reduction obtained (8%) is linked to the share of construction and dismantling (16% and 3%, respectively) for climate change indicator.

Table 10. Sensitivity analysis on the diesel consumptions at mines.

Mine type	Unit	Minimum	This study	Maximum
Open-pit mines		0.009	0.015	0.021
Underground mines	m3 diesel/kg U_3O_8	0.002	0.004	0.007
ISL mines		0.001	0.002	0.007

Influence of annual production on the climate change indicator. Based on data from 2019, default electricity production of the nuclear fleet was estimated to 380 GWh per year. A 10% variation on the total electricity production would change the results of the climate indicator by about 3%.

We can conclude that the order of magnitude of the result on the climate change indicator has little sensitivity to the variation of the main parameters.

5 Discussion

5.1 Comparison of the results on climate change with other assessments in the literature

Table 11 presents the impact of nuclear electricity on climate change based on literature review. The results range between 3 and 24 gCO_2eq/kWh, but converge towards 4–6 gCO_2eq/kWh, values close to the one found in this study (3.7 gCO_2eq/kWh). The result of this study is therefore in the lower range of LCA studies on nuclear power conducted so far (low GHG emissions intensity from supply stages, especially enrichment).

(The review is non-exhaustive. Only the most recent publications were considered)

5.2 Study limitations and knowledge gap for future studies

Although efforts were made to be as exhaustive as possible in collecting the most up-to-date data, this EDF LCA study has some limitations. Several simplifications of the nuclear cycle were made in the modelling, in particular for the fabrication of depleted uranium necessary for MOX, which is based only on the transport of uranium. This leads to an underestimation of the climate change indicator by 0.08%. Similarly, defluoridation of depleted uranium was modelled based only on transport; due to a lack of data, the corresponding plants were not included. The climate change impact is evaluated to be underestimated by 0.07% of the total result. Furthermore, very little specific data could be collected for the mining stage, as the ecoinvent data are outdated (1980s), while mining is what contributes the most to all indicators.

The end-of-life stage of nuclear power generation covers the storage of all radioactive waste (VLLW, LILW-SL, HLW & ILW-LL). In this LCA study, the storage stage represents a very small contribution to the impact of the nuclear power. However, the LCA modelling behind it is based entirely on the ecoinvent proxies. Furtherly, the land use indicator was not assessed in this study, while the impact of the surface of land occupied by the stored waste might bear an impact if proper data are collected and used. An LCA study should be conducted in future together with nuclear waste management operators to collect specific data and better assess the impact of the end-of-life of nuclear waste.

The impact assessment was carried out using only the ILCD indicators level I and II, based on their level of reliability and robustness, following the objectives of the study. Other factors were addressed using a flow indicator, either because they are not covered by ILCD indicators (waste, which is outside the scope of LCA), or because the associated indicators are still under development (water indicator, robustness of III). Finally, some indicators are not covered in the study, for land use and freshwater ecotoxicity, the methods behind were burdened with a high uncertainty (robustness of III for land use and II/III for ecotoxicity).

Future studies on the potential environmental impact of nuclear power should address these limitations by collecting more specific data on uranium mining and processing, as well as storage of waste at the end-of-life and investigate the indicators that could not be covered here: water use, land use, and freshwater ecotoxicity.

6 Conclusion

The purpose of this LCA study was to broaden the scope of knowledge on the potential environmental impact of nuclear power generation over its entire life cycle. The specific objectives of the study were to propose a life cycle inventory of the EDF nuclear power, to assess its potential environmental impacts on selected indicators with emphasis on climate change, and to build a base that can be used for further research.

In conformity with the objectives, this study enabled all the EDF divisions to increase their knowledge of the potential environmental impacts of their supply chain through the LCA methodology, resulting in a comprehensive life cycle inventory of the French nuclear fleet. The main strength of this LCA is the extensive data collection covering the entire French nuclear fleet, the second largest in the world. The results showed that mining and milling of uranium is the most contributing stage for LCA indicators (36% on climate change), except for ionizing radiation. The electricity production stage at EDF often comes as second most contributing stage, together

Table 11. Other LCA results of the impact of nuclear electricity on climate change.

Source	gCO_2eq/kWh	Comment
[33]	16 (50th percentile)	International; min 1, max 120
[34]	12 (median)	International; min 4, max 110
[35]	3–24	International
[9]	5	France, 2014
[10]	6	Switzerland, 2018
[11]	4	EPD, 2020
[21]	4	France, 2020
[36]	5	Europe, 2021
[12]	6	International

with the spent fuel treatment. The total impact of nuclear power on climate change (3.7 gCO_2eq/kWh) is in the lower range compared to studies published so far, as their results ranged from 3 to 24 gCO_2eq/kWh. Ionizing radiation is one of the analyzed LCA indicator, but this impact was treated also using a semi-qualitative approach. The direct emissions of carbon 14 and radionuclide emissions are permanently monitored. The semi-qualitative analysis based on the monitoring shows that the emissions are below the exposure limits legally defined.

In terms of recommendation, further effort should be done to collect more recent data from mining and milling, as well as to establish a collaboration with nuclear waste management operators to better capture the impacts at the end-of life. One of the most valuable outputs of this study is the detailed LCA model in Simapro software, which can be updated in the future.

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Conflicts of interest

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Data availability statement

Data associated with this article is not available online for legal reasons, but may be provided upon request.

Author contribution statement

Denis LeBoulch: Conceptualization, Data curation, Methodology, Software, Writing – review & editing, Validation. Vincent Morisset: Writing – review & editing. Zoé Jobard: Writing – original draft. Alexis Burguburu: Writing – original draft. Magdalena Czyrnek-Delêtre: Formal analysis, Project administration, Validation, Writing – review & editing.

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