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Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles

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ABSTRACT

Energy perspectives for the current century are dominated by the anticipated significant increase of energy needs. Particularly, electricity consumption is anticipated to increase by a factor higher than two before 2050. Energy choices are considered as structuring political choices that implies a long-standing and stable policy based on objective criteria. LCA (life cycle analysis) is a structured basis for deriving relevant indicators which can allow the comparison of a wide range of impacts of different energy sources. Among the energy-mix, nuclear power is anticipated to have very low GHG-emissions. However, its viability is severely addressed by the public opinion after the Fukushima accident. Therefore, a global LCA of the French nuclear fuel cycle was performed as a reference model. Results were compared in terms of impact with other energy sources. It emphasized that the French nuclear energy is one of the less impacting energy, comparable with renewable energy. In a second, part, the French scenario was compared with an equivalent open fuel cycle scenario. It demonstrates that an open fuel cycle would require about 16% more natural uranium, would have a bigger environmental footprint on the "non radioactive indicators" and would produce a higher volume of high level radioactive waste.

1. Introduction

Energy perspectives for the current century are dominated by the anticipated significant increase of energy needs due to the population growth and the likely economic development of emerging countries. In general, whatever the economic scenario, electricity consumption is anticipated to increase by a factor higher than 2 before 2050 due to the shift of fossil energy towards electricity [1]. Furthermore, the global climate change has now been proven to be partially related to the release of GHG (greenhouse gases) from anthropogenic activities, including energy production. Considering that about 80% of our current primary energy comes from fossil energies, we have to face in the near-future a challenging issue: meeting the increasing energy needs while curbing the GHG emissions. This implies a reduction in our dependence to fossil fuels. Nuclear power is anticipated to have very low GHG-emissions (usually in the range of 6–10 gCO_2eq/KWh_e) [2,3], and its development could therefore contribute to GHG-emissions reduction. Over the past 30 years, nuclear power has also demonstrated its capacity to produce base-load electricity at a low, predictable and stable cost due to its low dependence on the uranium price. Furthermore, natural uranium resources are widely distributed in opposition to fossil fuels. Hence, it is likely that uranium mining would not yield to significant international tensions and crisis as it has been the case for oil or gas. From this perspective, nuclear energy is considered as a potential contributor to the future energy portfolio to meet the energetic needs while preserving the climate.

However, from another perspective, the viability of nuclear energy is severely addressed by the negative public opinion after the Fukushima accident, in particular in Western European countries. The public opinion strongly believes that the accident has important consequences to population health and the environment. The accident has generated mistrust about the capacity to control nuclear reactors under extreme conditions, like the ones originated after the earthquake and the subsequent tsunami. This situation clearly stresses the fact that any choice in the energy mix and in particular dealing with nuclear energy the considerations go beyond the technical aspects, and it requires a wider general

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societal debate, in terms of environmental economical and societal implications. Energy choices are considered as structuring political decisions that imply a long-standing and stable policy based on objective criteria. Sustainability indicators are among the most relevant criteria to consider.

Sustainable development has been defined as early as in 1987 by so so-called Bruntland commission, as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4]. It has been soon recognized that it has to be promoted by combining three competitive simultaneous objectives which are the economic development, social development, and environmental preservation. Translating this general concept in practical and quantified objectives can be an indefinite matter of debate. Numerous sustainability indicators have been developed and proposed by economics or system ecologists to attempts ranking a given system and compare it to others in terms of sustainability (see for example [5–7]). However, many indicators are not yet internationally agreed upon and are for some of them not easily and objectively quantifiable, for instance in the societal field [8–10]. Furthermore, beyond the individual and elementary indicators, there is a real need on composite indicators, named indices, which can be more easily handled by the stakeholders. However, deriving indices is also a matter of real debate on the way to aggregate numerous and heterogeneous criteria in a limited number of upper-level indices [5].

Life cycle assessment (or life cycle analysis, LCA) is the main basis for deriving relevant and integrated indicators and has been widely applied to different energy sources, such as wind power, hydroelectricity, biomass, photovoltaic energies [2,9,11–13]. Several studies have also addressed the specific case of a target system (for instance a major city) and attempted to rank the different types of energy sources in order to derive the most "sustainable" one [14]. However, very few studies have dealt with the specific case of nuclear energy, with a wide range of results, depending on the chosen nuclear fuel cycle scenario [15–18].

The originality of this study is the comparison in terms of environmental impact through LCAs between the French nuclear fuel cycle and an open fuel cycle scenario leading to the same energy production with the same nuclear facilities from the mining to the repository. The LCAs were performed thanks to an homemade tool, NELCAS, which allows life cycle assessment to be performed on nuclear energy systems derived from the French nuclear fuel cycle. In this sense, France lies in a specific position because of the development of a complete fuel cycle industry through the so-called TTC (twice-through cycle). Therefore, NELCAS database has been fed with information coming from all the steps of the French nuclear fuel cycle and further extended by using the CEA expertise on scenario system studies.

This paper describes first the French fuel cycle, and presents the indicators and the methodology applied to perform the LCAs. Then, the results of the LCA of the French nuclear fuel cycle are discussed and the indicators are compared in terms of impact with other energy sources. In a second part, the current French fuel cycle and the open fuel cycle, also called OTC (once-through fuel cycle) are compared.

2. Synthetic presentation of the French energy system

France decided to develop nuclear energy after the first oil crisis in 1973. The first PWR (pressurized water reactors) started in 1977 (Fessenheim) and 58 PWRs were progressively connected to the grid up to 1999. This has allowed France to increase the proportion of electricity coming from nuclear reactors up to roughly 80%, decreasing its dependence on fossil energies. Subsequently, it has allowed France to decrease its CO_2 emissions for electricity production by roughly a factor of five, with a mean CO_2 emission in the range of 70–100 gCO_2/KWh since 1993 [19][a]. A value of 79 g/KWh is given for 2010, to be compared with the average EU emissions of 347 gCO_2/KWh [19][b]. The total nuclear installed capacity in France in 2013 is of 63 GWe for a total production about 400–420 TWh_e/year [20].

In parallel, through its two major industrial operators, EDF and AREVA, France has developed and mastered a complete fuel cycle which is completely located in France except for the ore-mining activities. Studies are also on-going for a potential geological repository to be opened in 2025 in Eastern part of Paris Basin (Meuse/Haute-Marne site). This section aims to briefly describe the specificity of the different fuel cycle steps. Fig. 1 synthesizes the main steps of the French fuel cycle with the reference annual fluxes. 2010 is taken as the reference year for the calculations because it is the most recent year for which the maximum of data is available.

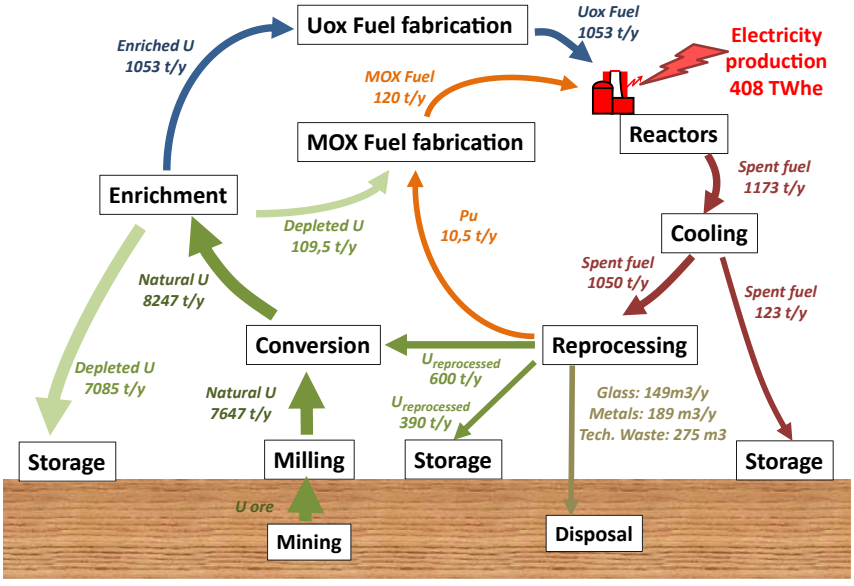

Fig. 1. French reference fuel cycle and its representative streams (year 2010).

2.1. Fuel cycle front end: from ore mining to fuel fabrication

Uranium is a natural and slightly radioactive metal available under different forms throughout the Earth's rock as well as in most rivers and in sea water. In specific geological conditions, uranium concentration is high enough to make the extraction technically and economically feasible. In-situ techniques (In-Situ Leaching technique-ISL) are mainly used for poor uranium ore (<0.1%) and when the ore mineralization is permeable enough and embedded between two impermeable geological layers. In other cases, classical excavation techniques are used, mainly open pit for shallow surface deposit (<120 m deep) and underground mines for deeper deposits. France roughly imports yearly 8000 t of uranium ore to feed its fuel cycle from these different kinds of mines.

After being mined, uranium ore is milled on site or close to the uranium mine. Uranium goes first through a mechanical treatment, crushing and grinding. Then, the uranium is extracted from the ore by leaching either with a strong acid or alkaline solution. Milling produces a uranium oxide (U_3O_8) concentrate (yellowcake) which generally contains more than 80% of uranium.

The yellowcake is further purified in France (Malvesi Areva site), converted into gaseous UF_6 in two steps (Malvesi and Pierrelatte sites) and then enriched in fissile isotope, ^{235}U (Tricastin site, close to Pierrelatte site).

Up to 2012, the enrichment was done by gaseous diffusion (Georges Besse I plant, GB I); it is now done by ultracentrifugation (Georges Besse II plant, GB II). Uranium is enriched in the range 3.5–4.5% of ^{235}U (to be compared to the initial 0.7%) and yields to the production of 7–10 times larger volume of depleted uranium which is not usable with the current reactor park and is stored as a strategic stockpile in Pierrelatte and in the Bessine site (Central part of France). In this study, only the former enrichment by gaseous diffusion was considered. It consumed a lot of energy: 2.4 MWh_e/SWU (A SWU is a Separation Working Unit which quantifies the work needed to produce enriched uranium at a given ^{235}U%, as a function of the ^{235}U% in the depleted uranium). However, since this enrichment uses nuclear electricity produced by the neighbour PWRs, its GHG emissions are much more limited than any other enrichment plants worldwide.

The enriched UF_6 is then converted back to UO_2 for the subsequent fuel fabrication at the Romans plant (Isère). Fuel pellets are manufactured from pressed UO_2 (uranium oxide) sintered at high temperature (>1400 °C). The pellets are then encased in Zirconium alloy (Zircaloy-4) tubes to form fuel rods, which are arranged into fuel assemblies ready for introduction into reactor.

2.2. Electricity production through PWR

The French utility EDF currently operates 58 s generation PWRs (34 of 900 MW_e, 20 of 1350 MW_e and 4 of 1450 MW_e) located on 19 sites. All these reactors belong to the same type derived from the former Westinghouse-type. However, their cooling system is different: 30 of them are cooled through cooling tower whereas the others directly use the adjacent river or sea water as a cold source.

Fuel burn-up is currently in the range of 45–50 GWd/t. In order to produce 400–420 TWh_e/y, roughly 1200 t of fresh fuel have to be yearly introduced in the reactor park. 1200 t of spent fuel are therefore discharged yearly.

2.3. Fuel cycle back-end: from fuel reprocessing to geological repository

Since the beginning of the nuclear energy development in the 70's, France has chosen to recycle the spent nuclear fuel with a twice-through cycle to recover uranium and plutonium. This recycling is operated successively in the La Hague plant (North-West of France) where uranium and plutonium are recovered by using a chemical separation process (PUREX process), and in the MELOX plant in Marcoule (South of France) where the plutonium oxide is used together with uranium oxide to produce MOX Fuel. The French policy aims to strictly balance the plutonium inventory which is recovered by the reprocessing with the one used to produce MOX fuel, so that no stockpile of pure plutonium is accumulated. Twenty-two 900 MW_e reactors are currently fuelled with one third of MOX fuel. As current PWR are not suitable for the plutonium multi-recycling due to their incapacity to fission the even isotopes of plutonium, irradiated MOX fuel is not reprocessed. Therefore, about 1000–1100 t of UOX fuel are yearly recycled, producing about 10 t of plutonium, recycled within 120 t of MOX fuel, and about 1000 t of reprocessed uranium, which still contain roughly 0.75% of fissile ^{235}U. 600 t of this reprocessed uranium are re-enriched to produce 80 t of re-enriched uranium oxide fuel (REU fuel). These operations are currently performed in the Seversk plant in Russia since the French gaseous diffusion enrichment plant (GB I) is not suitable for this operation. Four reactors are fuelled with REU fuel. Due to the possibility of GenIV reactor to burn any uranium isotopes uranium (i.e. depleted and reprocessed uranium), the remaining reprocessed uranium is stored as strategic material and is not considered as a waste.

The recycling operations produce also HLW (high level waste) conditioned in the dedicated R7T7 nuclear glass. Its composition has been designed to provide a long-term durability consistent with the embedded long-lived radionuclides. ILW (intermediate activity long-lived wastes-LL) are also produced in the form of compacted waste from hulls and end-pieces of the fuel assemblies and cemented waste (technological waste).

According to the French Act of June 28th 2006 on radioactive waste and nuclear material management, these wastes have to be disposed of in a deep geological repository. A potential site is under study since early 2000's in the eastern part of Paris basin (Meuse/Haute-Marne site) and should be proposed for a licence application by 2015. Repository operations are planned to start in 2025. The disposal is anticipated to be located in a Callovo-Oxfordian clay formation at 500 m depth. Repository is designed to accommodate the total stockpile of HLW and ILW-LL produced by the former and current reactors, up to their end of life. The repository is anticipated to be in operation for about one century.

3. Life cycle assessment of the current French nuclear fuel cycle

3.1. Selected indicators

A life cycle assessment requires the selection of relevant representative indicators. The selection of such key indicators could be difficult to achieve due to their large dispersion in the literature. Therefore, we restricted our assessment to a limited panel of indicators that were chosen based (i) on their dissemination and acceptance within the overall scientific community and (ii) on their widen applicability for the different energy sources.

Eight indicators have been selected to describe the non-radioactive impacts. They are the green-house-gases emissions (GHG, gCO_2eq/kWh_e) [13,21], the atmospheric pollution (SO_x and NO_x, mg/kWh_e) [21], the water pollution (mg/kWh_e) [21], the land-use (m^2/GWh_e) [13], the water consumption and withdrawal (L/MWh_e) [13,22], and the production of technological waste (g/MWh_e) [23].

Three indicators were selected addressing the radioactivity specificity. They are the radioactive gaseous and liquid releases (Bq/kWh_e) and the solid radioactive waste production (g/MWh_e or $m^3/$

MWh_e) [21]. The footprint of the required repository is also considered.

Five additional indicators have been also considered even if they do not fully fulfil the indicator selection criteria but they are frequently used in the literature since they help to better assess the impact of some liquid or gaseous releases in the environment. Indeed, knowing the amount of SO_x and NO_x in the environment does not inform on the potential consequences of such releases whereas acidification, eutrophication and POCP (photochemical ozone creation potential) phenomena are clear indication of the consequences of such releases [24,25]. Similarly, eco-toxicity and human toxicity was used to assess the maximum potential impact of both chemicals and radioactive release on environment and human beings [26]. These indicators were established by directly converting the total amount in potential impact through the specific impact factor expressed in internationally agreed units that allow further comparison with other systems. Reference is frequently made to "potential impact" indicators, as opposed to "actual impacts". This is because characterization models do not allow real impacts to be assessed since these are dependent on actual local conditions of pollutant emission and dispersal at the time and place of the release. As such, these indicators inform on the maximum impact that such a release could generate, which is obviously an overestimation.

3.2. Methodology

The classical PCA (Process Chain Analysis) approach of LCA (life cycle assessment) has been applied by considering (i) the annual emissions, (ii) the penalty coming from the plant construction averaged on its whole lifetime, (iii) the penalty coming from its cleaning and decommissioning (from cradle to grave) and (iv) the transports between all the fuel cycle facilities. The analysis was performed on a yearly basis for the whole French nuclear fuel cycle and was limited to the "first order contributions". It does not describe the full chain of any technological sub-system. For instance, contributions coming from the use of concrete to build any plant were considered. However, contributions related to the construction of the trucks that were used during the construction of the plant were not considered. For all the facilities (fuel cycle plants or reactors), their lifetime was assumed to be 20 to 50 years, which is likely a conservative assumption for most of them. Contributions from the construction and dismantling of the plant were systematically considered. Regarding the dismantling of the facilities, very few data are already known and we had to estimate the deconstruction data on the basis of a percentage of the construction data, from 35 to 50% defined according our own expertise. In order to simplify the calculations, it is assumed that the French reactors park is only fed by the AREVA front-end plants, which is only true for about 80–90% of the flux. The reference year was 2010, since it is the last year where we could compile the entire set of data for the whole cycle.

All the data used in the calculations were taken from the available public data. In particular, the yearly environmental reports of each of the French nuclear facility were intensively used to get data about the annual energy and chemicals consumption as well as the production of any type of waste. Publically-available data on the plant designs were used to assess the total volume of materials used for their construction [18,27]. When data were not available for this year, the most recent data from the literature were used. Indicators were normalized to the 2010 nuclear electricity production which was 408 TWh_e. Information, references and specific assumptions are given in Table 1. GHG emissions and atmospheric pollution (SO_x and NO_x emissions) have been estimated by converting the mass of materials used to produce gaseous emissions using the reference conversion factor for each of these materials [24,25,28,29]. Nuclear waste volumes and streams were estimated based on the French national nuclear waste inventory [30,31]. Finally, missing data were extrapolated from the closest available data in order to avoid neglecting any specific item using the CEA expertise in system studies.

3.3. The NELCAS tool

Calculations were performed by using the Nuclear Energy Life Cycle Assessment Simulation tool, NELCAS. NELCAS is a homemade simple simulation tool which is based on MS Excel sheets. It compiles and relates together all the energy and matter fluxes along the nuclear fuel cycle. It does not aim to replace the existing exhaustive and detailed LCA code (as SIMAPRO for instance), but has been specifically developed to draw a global footprint assessment of the French nuclear energy system taken as a representative situation of a nuclear country. It also allows the calculation of any scenario that would be derived from the French one.

3.4. Results for the environmental and technological impact indicators

Table 2 and Fig. 2 gather the results for the different environmental and technological indicators. GHG emissions come mainly from mining, reactors operation and disposal steps. SO_x and NO_x emissions, water pollution and land use indicators are driven by the mining operations whereas water consumption and withdrawal and technological waste indicators are driven by the reactor operation step.

3.4.1. Green house gases emissions

The total GHG emissions for the global fuel cycle are estimated to be 5.29 gCO_2eq/KWh_e, in the lower range of usual reference data [2,3,17,53–55]. The main contributions come from the reactors operation (40%), the mining activities (32%) and the enrichment (12%). On the other hand, conversion, disposal and reprocessing operations account respectively for 5, 2 and 7%, whereas fuel fabrication has negligible impact. These results are consistent with those from the literature except for the enrichment step which is much lower than existing figure (typically between 1.8 and 16 gCO_2/KWh_e [54],). This discrepancy is explained by the fact that the French enrichment plant is fed by 3 on-site nuclear reactors, with very low GHG emissions. As an example, the supply of all enriched uranium by the coal power USEC plant alone would raise the total for the enrichment step up to 55 gCO_2eq/KWh_e [2].

3.4.2. Atmospheric and water pollution

SO_x and NO_x emissions are in the range of the data published in the literature [2,3,55]. The main contributor is in both cases the mining activities which represents about 87% for SO_x and 78% for NO_x. The other contributors are by decreasing order, the reactors (6% for SO_x, 11% for NO_x), the enrichment (3% for SO_x, 4% for NO_x) and the reprocessing (3% for SO_x, 2% for NO_x). Releases of chemical hazards (excluding radioelements) in water can lead to water pollution. These releases are mainly produced by mining and milling operations (89%), with a significant contribution of sulphates. The second contributor derives from the reactor occupation (8%) and then reprocessing (2%).

3.4.3. Land-use

The land-use appears to be in the mid-range (211 m^2/GWh_e) of already published data (from 50 to 500 m^2/GWh_e) [2,3]. Mining and milling activities are calculated to be 68% of the total land-use for the whole fuel cycle, the second contribution being the reactors

Table 1
The different steps of the fuel cycle with assumptions made and references used for building the LCA NELCAS database..

	Site	Operation	Ref.
Front-end of the fuel cycle	Mines (Areva Production): • Canada (33%, open-pit & underground) • Niger (26%, open-pit & underground) • Kazakhstan (41%, ISL)	Data from AREVA reports (50%, "TSN" report and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report), Katco (20%), CAMECO, Vattenfall, Ecoinvent. When data not available for a mine on an indicator, data from same type of mines were taken instead.	[32–36]
	Malvési (Narbonne)	Data from AREVA reports (80%, "TSN" reports and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report) and Société française de chimie (20%) GHG emissions are calculated based on the energy consumptions and using the reference conversion factors. All data taken from their environment annual report	[36–38]
	Tricastin (Pierrelatte)	Data from AREVA reports (90%, "TSN" reports and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report). Additional data from www.francenuc.org, www.world-nuclear.org, and Société Chimique de France. Several plants are gathered on the same site. All the figures were attributed to enrichment step since enrichment is the most important activity. Enrichment is performed by gaseous diffusion, with a high energy consumption produced by the neighbour PWRs. We therefore use the GHG emissions factor for nuclear energy to estimate the GHG penalty.	[36,39]
	Romans	Data from AREVA reports (80%, "TSN" reports and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report) and Société française de chimie (20%) The total fuel inventory needed to feed the French reactor fleet is supposed to be totally produced by this plant (fuels bought by EDF to foreign companies is hence not considered)	[36,40]
Energy production	58 Reactors on 19 production sites	Data from EDF (power plants TSN reports, environmental reports,…) and Vattenfall environmental reports For water withdrawal, the reference values of 6 m^3/MWh_e for reactors with cooling towers and 160 m^3/MWhe for reactors without cooling towers were considered. 53% of installed power corresponds to reactors with cooling tower.	[41,42]
Back-end of the fuel cycle	La Hague	Data mainly from AREVA reports (90%, "TSN" reports, "Spent Nuclear Fuels Reprocessing France" Apr 2008 report and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report)	[30,31,36]
	Melox (Marcoule)	Data mainly from AREVA reports (90%, "TSN" reports and "Document de référence AREVA 2010 – Propriétés immobilières, usines et équipements" report)	[36,43]
	Storage/Disposal: Aube (VLLW, ILW-SL) Meuse-Haute Marne (CIGEO project for an underground long term disposal site for ILW-LL and HLW)	Data derived from ANDRA (underground disposal reports 2005 et 2009 and "CS TFA 2009" and "CS FMA 2010" reports), Land use was calculated by taking into account the total surface of each site or the anticipated surface for the HLW site. GHG, SO_x, NO_x emissions were assessed by considering the concrete, the steel, the copper and aluminium used for construction of surface buildings, the excavated earth, the use of building machines, like for other plants of the fuel cycles. Results in mass were converted in volume using a density of 2.8 for cemented and glass wastes, 6.5 for hull containers.	[30,44–47]
Transporta-tions	Between every sites described above	The direct and indirect contributions of transportations were considered (emissions of GHG, SO_x, NO_x,…). In order to assess the total distance, the distance between each successive site in the fuel cycle was determined by using the Google maps route calculator for road or railway (.https://maps.google.com/) and the Google map distance calculator for shipping (http://www.daftlogic.com/projects-google-maps-distance-calculator.htm), adjusted according the best sea route it is possible to follow. The most relevant or dominant transport mode was selected for each type of trip (boat, train, truck).	[24,25,27–29,48,49]
Construction, dismantling		Data derived from EcoInvent, CEA system studies, ANDRA Inventaire déchets 2009.	[18,27,50–52]

Table 2
NELCAS results for the environmental and technological impact indicators for the French TTC..

	GHG	Atmospheric pollution SO_x	Atmospheric pollution NO_x	Water pollution	Land-use	Water consumption	Water withdrawal	Technological waste
	(gCO_2eq/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(m^2/GWh_e)	(L/MWh_e)	(L/MWh_e)	(g/MWh_e)
Mining	1.704	14.242	19.73	263.072	144.1	17	17	1.5
Conversion	0.278	0.058	1.04	0.087	1.82	4.6	4.6	2.0
Enrichment	0.626	0.547	1.06	2548	1.88	23	23	0.65
UOX fabrication	0.035	0.013	0.05	0.021	0.93	0.2	0.2	0.23
Reactors	2.140	0.938	2.84	16.366	45.1	1460	72.318	20.15
Reprocessing	0.376	0.484	0.50	5433	4.98	1.7	1.7	0.63
MOX fabrication	0.027	0.004	0.035		0.13	0.1	0.1	0.18
Disposal	0.104	0.024	0.097		12.01	0.1	0.1	1.11
Total	**5.29**	**16.276**	**25.30**	**287.53**	**211.0**	**1507**	**72.364**	**26.4**

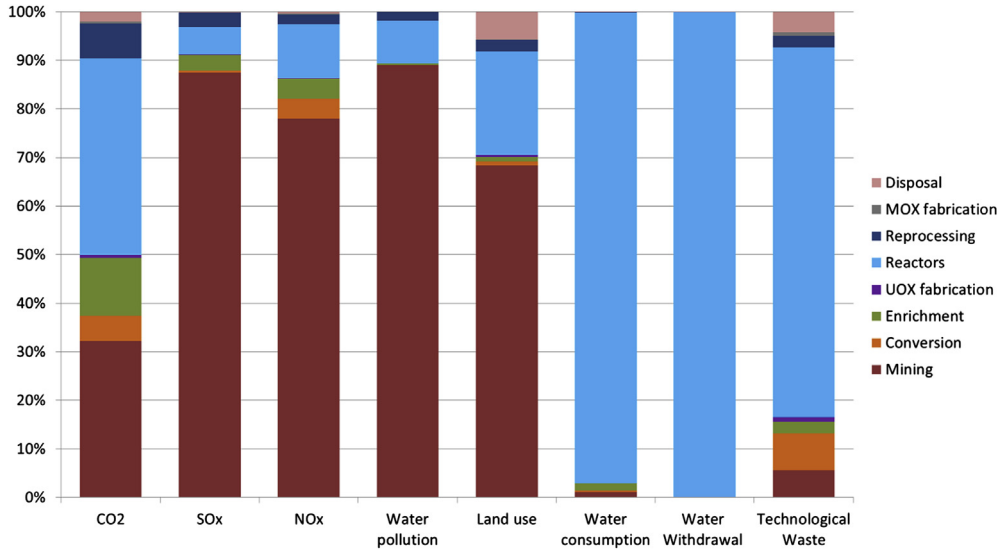

Fig. 2. Relative contribution of each step of the fuel cycle to the environmental and technological impact indicators calculated with NELCAS for the French TTC.

sites (21%). Actually, 75% of the uranium used in the French fuel cycle comes from underground mines which have a typical land-use indicator two orders of magnitude lower than the one of open-pit mines. It is also noteworthy that the final geological repository represents only 6% of the total land-use indicator, due to its averaging on the whole lifetime of any fuel cycle plants. The other fuel cycle activities play a minor role.

3.4.4. Water consumption and withdrawal

Reactor cooling is the main contributor to water consumption (97%) and withdrawal (99.9%), although on the reactors with cooling tower (53% of the French reactors) are the only ones with net water consumption (1500 L/MWh$_e$). The front-end operations (mining, milling, conversion and enrichment) are the main second-order contributors ($\sim$45 L/MWh$_e$, i.e. 96% if reactor cooling is not considered) whereas water consumption and withdrawal is negligible at the back-end ($<$2 L/MWh$_e$). However, water consumption from front-end activities has to be carefully considered since these activities are often located in arid areas where preserving available water is a key issue. Furthermore, depending on the type of mining activities, these figures can be much higher since the use of ISL techniques consume larger amount of water [56].

3.4.5. Natural resource efficiency

In the twice-through fuel cycle, 7647 t of natural uranium are needed to produce the annual 408 TWh$_e$. The natural resource efficiency is therefore 53.4 GWh$_e$/KU$_{nat}$. This figure is important in order to compare the different fuel cycle scenarios.

3.4.6. Discussion on the environmental impact of the French TTC

The values calculated in this study for the environmental indicators are in the range of data already published in the literature, most of the time a little bit lower than the average data [2,3,17,18,53–55,57]. This is obviously significant for GHG emissions (5.29 gCO$_2$eq/KWh$_e$ for a range of 3–35 gCO$_2$eq/KWh$_e$) with peaks at about 200 gCO$_2$eq/KWh$_e$. The highest published values often came from the combination of the more pessimistic data for each step of the fuel cycle. Actually, in some scenarios, authors considered mines with a uranium grade 1 or 2 order of magnitude lower than the mines considered here. Applied to the French scenario, this would increase the contribution of the mining alone up to 20 or even 200 gCO$_2$eq/KWh$_e$. In addition, In the French fuel cycle, most energy consumed to operate the facilities (but mining) is mainly nuclear electricity, lowering therefore the emission of GHG, NO_x and SO_x. As already mentioned, the French enrichment step has a low impact (0.63 gCO$_2$eq/KWh$_e$) since three nuclear reactors have been dedicated to providing electricity to the enrichment plants. This has to be compared to coal fed enrichment plants (up to 80 gCO$_2$eq/KWh$_e$) [53]. Moreover, La Hague plant reduced by 25% its GHG emission between 2008 and 2010 by replacing fuel boilers by electric ones (operated with nuclear electricity) [31]. At Tricastin, specific actions were undertaken to reduce volatile organic compounds releases [39]. Finally, part of this difference could also be related at a lower extent to the simplification used in this study by neglecting the second or third order contributions but the thorough analysis that was performed for each indicator guarantees a limited impact of this simplification. Atmospheric and water pollution and land-use are mainly driven by the front-end activities whereas water withdrawal and consumption and technological waste are driven by the reactor operation. The back-end of the fuel cycle has a limited impact, except on GHG emissions (>30%).

3.5. Results for the additional potential impact indicators

The results obtained for the additional potential impact indicators are given in Table 3 and Fig. 3

3.5.1. Acidification potential

Acidification depends mainly on SO_x and NO_x emissions. This indicator represents the impact of the studied system on acid rain formation. It is given in mg SO_2 equivalent/kWh$_e$. Mining activities are the main contributors to the acidification potential (82%), followed by reactor operation (8%). The remaining 12% are shared almost equally between the rest of the activities (2–4% per activity). SO_x and NO_x generation contribute equally to this indicator even if generally, more NO_x are produced. Actually, a corrective factor of 0.7 is to be applied to NO_x data to get the SO_2 equivalent impact [25].

3.5.2. Eutrophication potential

Eutrophication is a phenomenon linked the increase in concentration of phosphorous and nitrogen compounds in aquatic

Table 3
NELCAS results for the additional potential impact indicators for the French TTC..

	Acidification potential	POCP	Eutrophication	Eco-toxicity	Human toxicity
	(gSO_2eq/MWh)	(gC_2H_4eq/MWhe)	(gPO_4eq/MWhe)	(g1,4-DCBeq/MWhe)	(g1,4-DCBeq/MWhe)
Mining	28.06	2.436	2.774	637.597	1225.207
Conversion	0.90	0.149	0.148	0.205	1348
Enrichment	1.25	0.055	0.918	0.229	1428
UOX fabrication	0.05	0.002	0.015	0.000	0.064
Reactors	2.89	0.151	0.760	0.005	4331
Reprocessing	0.84	0.039	0.583	0.185	0.779
MOX fabrication	0.03	0.001	0.005	0.000	0.043
Disposal	0.09	0.007	0.013	0.000	0.124
Total	**34.10**	**2.840**	**5.215**	**638.221**	**1233.32**

media and NO_x in the atmosphere. It leads to the proliferation of some seaweeds which asphyxiate the ecosystem. It is given in mg PO_4^{3-} equivalent/kWh_e. As for acidification, mining is the main contributor (53%), followed by enrichment (17%), reactors (14%) and reprocessing (11%). Only conversion and disposal contribute for respectively 3 and 4%. In the fuel cycle, NO_x are the main contributors to eutrophication (92%).

3.5.3. POCP (photochemical ozone creation potential)

Tropospheric ozone formation is mainly associated to photochemical pollution (smog). This indicator depends on SO_x, NO_x and VOCs. It is given in mg C_2H_4 equivalent/kWh_e. Mining is the key contributor (85%). Other cycle activities account for 1–5%. In addition to SO_x and NO_x that account respectively for 28 and 23%, dodecane used at the milling contributes for 49% because of its high conversion factor into C_2H_4 equivalents (0.577 compared to 0.048 for SO_x and 0.028 for NO_x [24]).

3.5.4. Eco and human toxicity potentials

Some chemicals releases can be toxic for human and other living species in the ecosystem. Calculations on a real system are more than complex. To ease this calculation, we have considered that liquid effluents were all released in freshwater. This simplification leads to an overestimation of the impact since this impact would be lower in sea water because of the dilution effect. They are given in mg 1,4-dichloro-benzene equivalent/kWh_e. Clearly, mining is the only contributor with more than 99% of the potential impact both for the eco and the human toxicity. Vanadium is the main contributor to the eco-toxicity potential (80%), followed by molybdenum (10%) and uranium (only 2.5%). Molybdenum is the main contributor to the human toxicity potential (63%), followed by selenium (17%), vanadium (16%), NOx (1.9%) and uranium (only 1.6%). In these two indicators, the potential impact is highly oriented by the conversion factors into 1,4-DCB (1,4-dichloro-benzene). Indeed, the high contribution of selenium to the human toxicity potential, which is however present at a very low amount, is explained by a very high conversion factor of 56,000, to be compared with a factor of only 12 for lead [26].

3.6. Results for the radioactive wastes

The outcome of the impact calculation for the management of radioactive waste is given in Table 4 and discussed below.

3.6.1. Radioactive gaseous and liquid releases

During the entire fuel cycle operations, radionuclides are released in the atmosphere and in aqueous media. The main contributor is radon and other noble gases; followed by tritium, then C14 and other radionuclides (Table 4). Radon, which is initially present at low concentration in the natural uranium ore, is considered to be only and totally released in the atmosphere during the mining and milling step (35 TBq/tUnat, [18]). It represents 53% of the radioactive gaseous emissions (Fig. 4). Noble gases, tritium and C14 are produced in the fuel by neutron reactions during reactor operation. Most of these gases remain trapped in fuel pins and are mainly released at the reprocessing step, except Tritium, which is slightly released in the reactor cooling system due to its diffusion through the fuel pin claddings. Small amounts of these gases are however released during reactor operations due to breached claddings. About 99.99% of the rare gases (554.5 kBq/KWh_e, 45% of the radioactive gaseous emissions) are released in the atmosphere following the shearing and dissolution of the fuel rods and only the remaining 0.01% is released in reactors. On the other hand, 99.2% of the tritium (27.1 kBq/KWh_e) is released as liquid

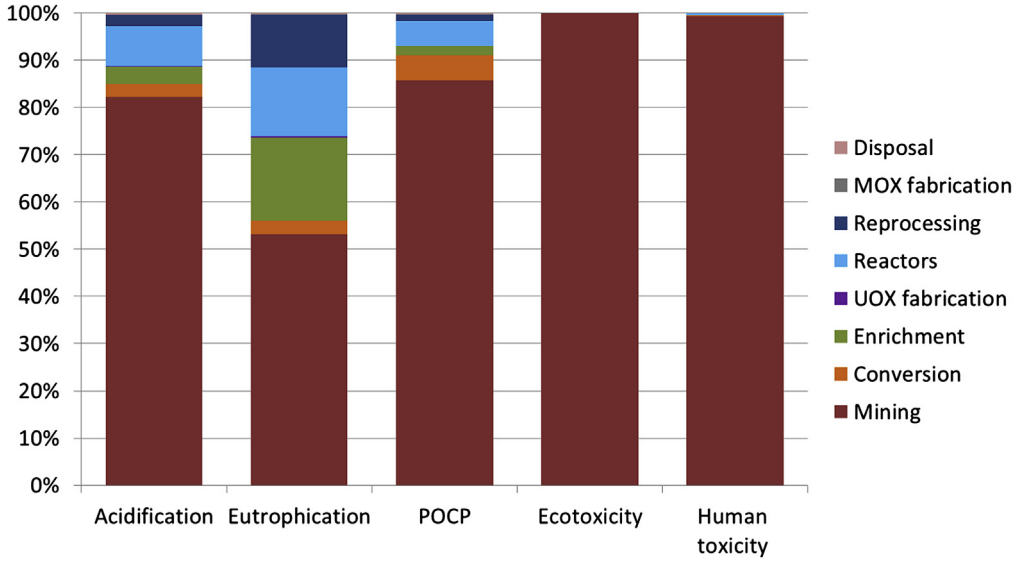

Fig. 3. Relative contribution of each step of the fuel cycle to the potential impact indicators calculated with NELCAS for the French TTC.

Table 4
NELCAS results for the radioactive impact indicators for the French TTC..

	Radioactive gaseous emissions	Radioactive liquid emissions	Radioactive solid waste			
			VLLW	ILW-SL	ILW-LL	HLW
	(Bq/kWhe)	(Bq/kWhe)	(m^3/TWhe)	(m^3/TWhe)	(m^3/TWhe)	(m^3/tTWhe)
Mining	666744		3190			
Conversion	1E-04	53.8	1.97	1.19		
Enrichment	5E-05					
UOX fabrication	2E-05					
Reactors	162	2717	22.94	24.61	0.32	
Reprocessing	554628	24444	2.63	4.31	0.80	0.36
MOX fabrication	2E-05	6,4E-05	0.019	0.1	0.05	
Total	**1221534**	**27215**	**3217.59**	**30.21**	**1.18**	**0.36**

wastes and represent 89.7% of these wastes. The partition in the cycle is as follows: 90% is released during reprocessing (24.4 KBq/KWh_e, 90%) and 10% in reactor operation. Carbon-14 and other minor radioelements represent only 0.01% of the gaseous and liquid radioactive releases (146 Bq/KWh_e). 50% are released during the reprocessing (73 Bq/KWh_e, equally shared between gaseous and liquid waste). It is noticeable that 37% (54 Bq/KWh_e) are released as a liquid waste during the conversion steps, during the yellowcake purification. Only 19 Bq/KWh_e are released in reactors as gases due to breached claddings.

It is noteworthy that these radioactive releases are well below the authorization and regulations thresholds and have a negligible effect on health as evidenced by the numerous health reviews around the La Hague Plant which demonstrate that the total impact is lower than 10 μSv/year [58]. In particular, noble gases are fully chemically-inert and do not interact with the biologic molecules: their environmental and human potential impact is therefore negligible around the plant [59].

3.6.2. *Radioactive solid wastes*

The handling of solid radioactive is one of the main challenges for the sustainability of nuclear energy. Nuclear waste is traditionally split into four categories, according to their radioactivity content and duration: (i) very low level waste, VLLW, (ii), short-lived intermediate level waste, ILW-SL, (iii) long-lived Intermediate level waste, ILW-LL and (iv) high level waste, HLW (Table 4, Fig. 5). Data concerning VLLW and ILW-SL have been taken in the ANDRA reports [30,44,45]. Data for HLW and ILW produced in La Hague come from the same reports whereas data on ILW produced by MELOX have been taken in their own environmental report [43]. VLLW and ILW are produced at the dismantling step at the end of life of each facility. Few nuclear facilities have been dismantled to date in France, therefore the data based on practical experiences are scarce. However, CEA has performed evaluation scenarios allowing a coherent estimation of the waste production coming from the cleaning and dismantling steps of nuclear fuel cycle facilities. According to these studies dismantling has almost no impact on VLLV volumes (1%), However it contributes to some 40–50% of the ILW.

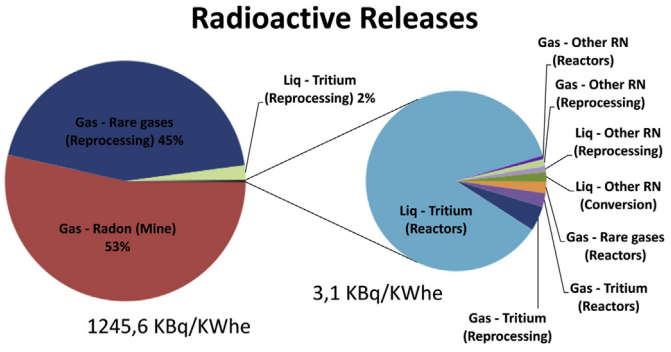

Fig. 4. NELCAS results for the radioactive releases indicator for the French TTC.

The main contributor to VLLW (3217 m^3/TWh$_e$) is mining (99%; mine tailings, leaching residues and residual waste). The next contributor is reactor operation with only 0.8%. Other fuel cycle operations do not produce significant amount of VLLW (0.2%). 1% of this total volume is foreseen to come from the dismantling of the facilities. The total volume of ILW-SL is 30 m^3/TWh$_e$. Reactor operation is responsible for 75% of the volume, reprocessing is 19%, front-end operations account for 5% and MOX fabrication with 1% of the total volume. The ILW-SL wastes are anticipated to be mainly produced during the dismantling of the fuel cycle facilities (65% of the total volume). The other significant contributors are reactor operation (20%) and La Hague plant operation (11%). The wastes under the ILW-LL category (1.18 m^3/TWh$_e$) come from the operations of the fuel cycle with 62% for reprocessing and 25% for reactors. The remaining 13% come from the MOx fabrication operations. Dismantling of reactors and La Hague plant at their end-of life is anticipated to contribute with 42% of the total volume. HLW (. A total amount of 36 m^3/TWh$_e$) are only produced by the spent fuel reprocessing operations. Fission products and minor actinides are vitrified and stored in nuclear glass wasteform in canisters. This information is clearly visualized in Fig. 4.

The way to manage each of these wastes is very different, both in terms of the timescales and the selected technical solution. In France, LLW and ILW-SL are stored on surface or sub-surface facilities whereas ILW-LL (compacted and cemented) and HLW (glass) are to be disposed of in underground repositories which are expected to be a scarce and expensive resource. It is therefore of paramount importance to address the repository footprint issue associated to the management of ILW-LL and HLW since unitary surface area by canister is very different from one type of waste to the other, and very strongly influence the overall footprint and cost. Considering an excavated volume of 55 m^3/glass canister (HLW), 7.3 m^3/compacted waste canister (ILW-LL) and 21.3 m^3/cemented waste canister (ILW-LL), the current French fuel cycle (TTC) requires 145 m^3/TWh$_e$ for a total ILW-LL and HLW volume of 1.53 m^3/TWh$_e$. It corresponds to a repository surface area of 215 m^2/TWh$_e$.

4. Comparison of NELCAS results with literature data on nuclear energy and with other energy sources

The good agreement between NELCAS results and published data on nuclear energy validate the methodology and the consistency and relevance of the wide set of data compiled in this study. Based on this assessment, NELCAS results have been also compared with data from the literature on other energy sources such as coal, oil/gas, hydro, wind, PV (photovoltaic), biomass, and also nuclear [2,8,11,12,15,17,53–55,57,60] (Fig. 6). In most cases, NELCAS results for nuclear energy are in the lowest range of variation for most of the indicators, often close to renewable energies. These results highlight again that nuclear energy has the lowest impact in terms of GHG emission (about 5.3 g/kWh$_e$), this is 100 times lower than fossil energy and 8 times lower than photovoltaic energy. When considering atmospheric pollution (SO_x and NO_x), nuclear energy has higher values than hydro and wind electricity, but still lower than PV and obviously fossil energies. Regarding potential impact indicators (acidification, eutrophication and POPC), nuclear energy figures are systematically in second best position, with impact higher than hydroelectricity but lower than any other energy sources, even

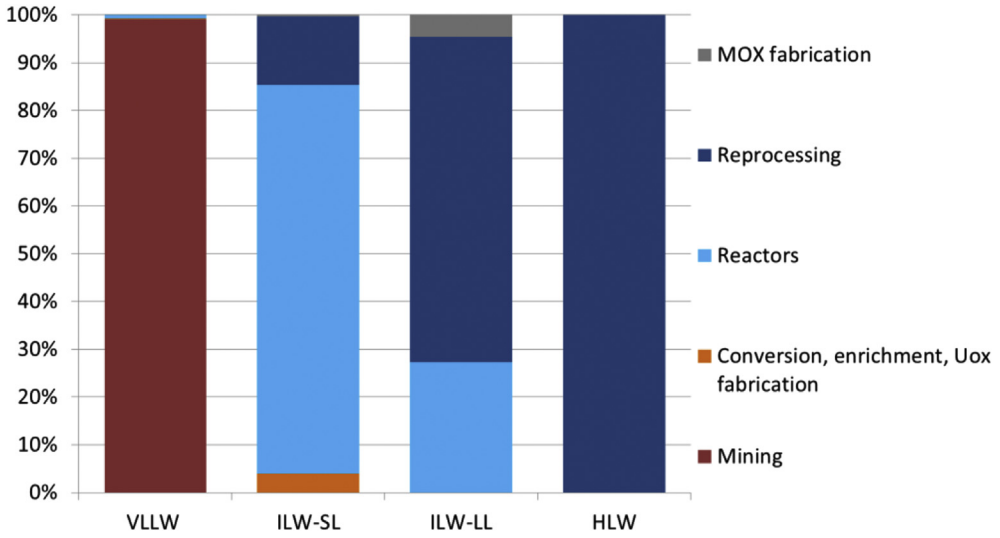

Fig. 5. Relative contribution of each step of the fuel cycle to the radioactive solid waste indicators calculated with NELCAS for the French TTC.

wind-power and PV. Similarly, although mining has a strong impact, nuclear energy land-use is anticipated to be the lowest. Conversely, figures for water consumption and withdrawal of nuclear energy are significantly higher than other energy sources, in the range of fossil energies. Finally, technological waste produced by nuclear energy is about 1000 lower than fossil energies but still remains 10 times higher than renewables. This is directly related to the large size of the infrastructures (plants…) which are needed to operate the whole fuel cycle (in particular the reactors).

5. Comparison between once- and twice-through fuel cycles

The NELCAS tool allows relating the energy and matter fluxes along the fuel cycle based on the French specific situation. Hence, It can also be predictively used to extrapolate the indicators values for various fuel cycle scenarios. In this framework, NELCAS tool was used to derive the likely indicators of an equivalent once-through cycle in which no recycling is operated and then to compare it with the reference twice-through fuel cycle.

5.1. Methodology for extrapolating the once-through cycle

The NELCAS model was modified to extrapolate a virtual situation in which France would produce the same amount of electricity with the actual reactor park but without operating any recycling operations. The calculations were performed by suppressing the treatment/recycling part of the fuel cycle and correcting the matter and energy fluxes all along the fuel cycle to produce the same

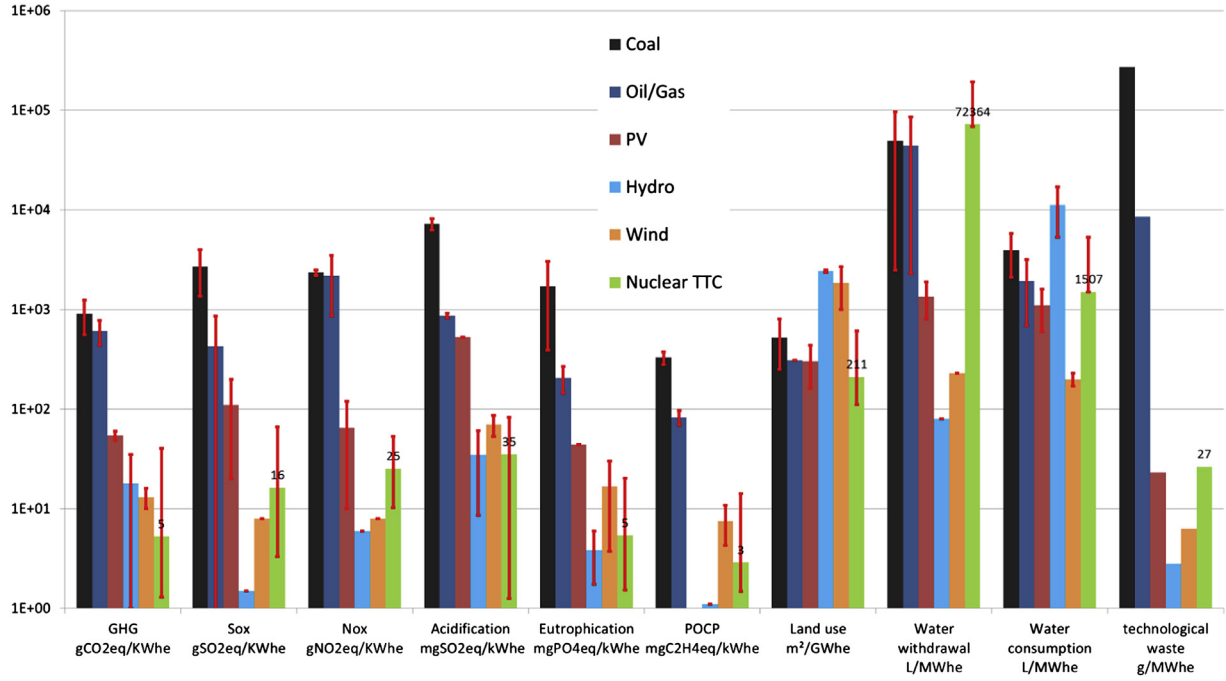

Fig. 6. Comparison of the selected indicators between the French TTC and other energy sources. The error bars represent the gap between the minimum and maximum values found in the literature.

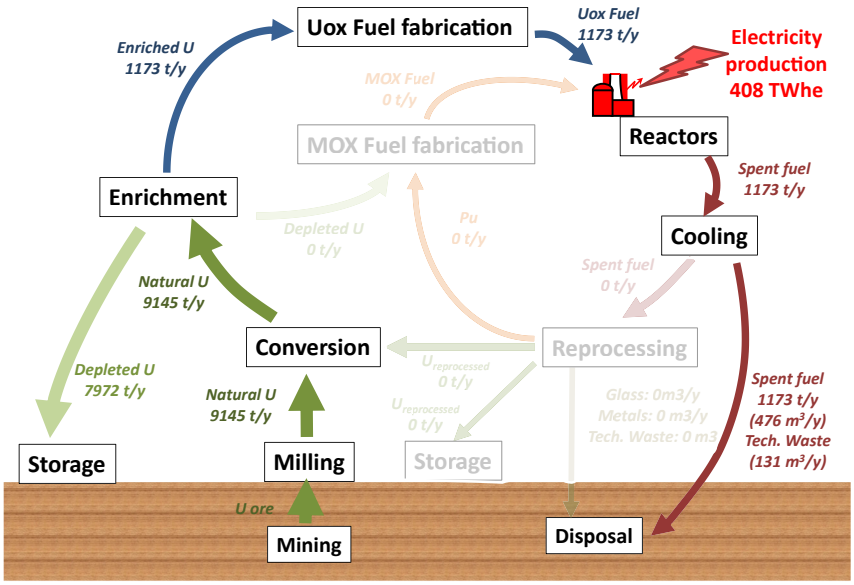

Fig. 7. Open fuel cycle derived from the French closed fuel cycles by suppressing the reprocessing, the amount of produced electricity remaining the same and its representative streams.

amount of electricity, all other parameters being equal (origin of uranium, electro-nuclear fleet, annual electricity production…). This scenario is illustrated on Fig. 7. Compared to the previous TTC scenario, all the spent fuel is considered as a waste to be disposed of (1173 t/year) and the need in natural uranium is subsequently increased (9145 t instead of 7647 t) to compensate the current use of plutonium and re-enriched uranium The type and amount of waste are also significantly different (see Fig. 8).

5.2. Comparison between once-through fuel cycle and current French twice-through fuel cycle

NELCAS results for the OTC are given in Tables 5, 6, and 7 They are not discussed in the details but the attention was focused to the comparison of the indicators between the TTC and the OTC.

Most of the environmental indicators are increased when shifting from the TTC to the OTC: GHG emissions, atmospheric pollution, water pollution, acidification, eutrophication, POCP, eco-toxicity, human-toxicity, land-use. This can be explained by the very significant contribution of the necessary increase in the mining, conversion and enrichment steps (front-end steps) to these indicators and low contribution of the reprocessing step. As mining is increased by ~17% and conversion and enrichment by 10% when shifting from twice-through to once-through, it obviously leads to a significant increase of these indicators.

Mining, conversion and enrichment are the main contributors to GHG emissions (50%) and atmospheric pollution (86–91%) whereas 7% or less come from the reprocessing. The environmental impact of GHG, NO_x and SO_x is then higher for the OTC. Water pollution is higher for the OTC (16%) as well as technological wastes (9%). This is explained by the fact that water pollution is driven by the mining and technological waste is the result of reactor operation and disposal. The potential impact indicators follow the trend of NO_x and SO_x except for eutrophication. Actually, its low change comes from a balance effect between releases from the reprocessing plant (0.58 gPO_4^{3-}eq/MWh_e) and releases from the front-end of the cycle

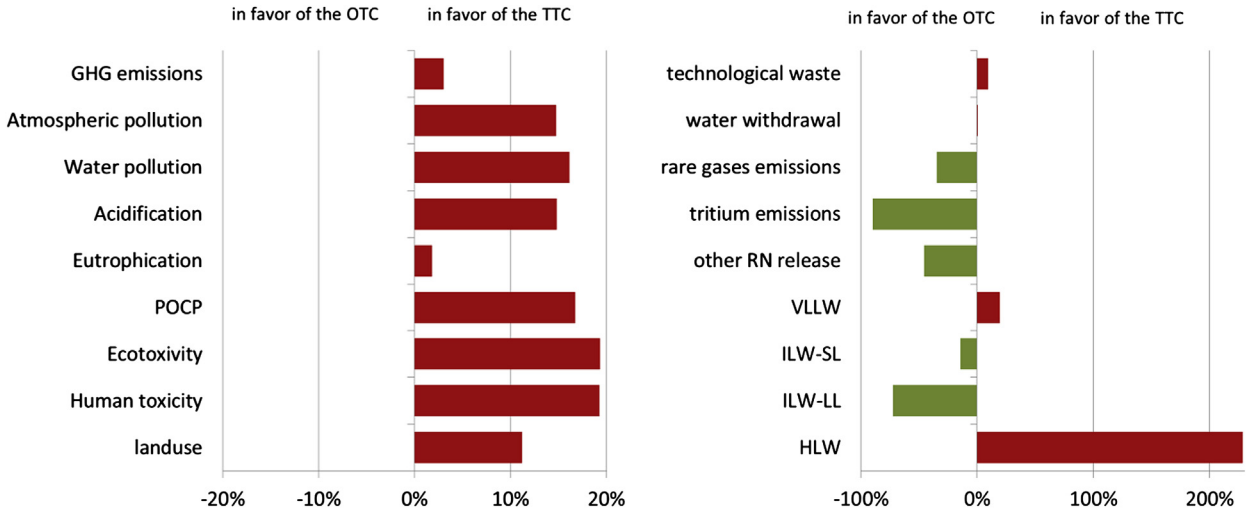

Fig. 8. Evolution of the impact indicators when going from the French TTC to an OTC producing the same amount of electricity with the same PWR fleet.

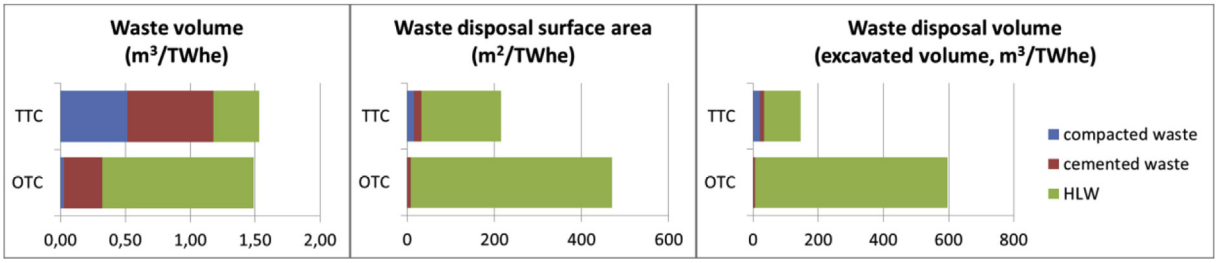

Fig. 9. Comparison of the waste volumes, waste disposal surface areas and waste disposal excavated volumes for the TTC and the OTC.

Table 5
NELCAS results for environmental and technological impact indicators for the OTC..

	GHG	Atmospheric pollution SO_x	Atmospheric pollution NO_x	Water pollution	Land-use	Water consumption	Water withdrawal	Technological waste
	(gCO_2 eq/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(mg/kWh_e)	(m^2/GWh_e)	(L/MWh_e)	(L/MWh_e)	(g/MWh_e)
Mining	2037	17.03	23.60	314.60	172.4	20	20	1.5
Conversion	0.308	0.06	1.16	0.10	2.0	5.1	5.1	2.2
Enrichment	0.696	0.61	1.18	2.83	2.1	25	25	0.7
UOX fabrication	0.039	0.01	0.06	0.02	1.0	0.2	0.2	0.3
Reactors	2141	0.94	2.84	16.37	45.1	1460	72,318	20.1
Disposal	0.227	0.09	0.239		12.0	0.1	0.1	4.1
Total	**5.45**	**18.73**	**29.01**	**333.92**	**222.6**	**1511**	**72,369**	**28.9**

Table 6
Results for the additional potential impact indicators for the OTC..

	Acidification	POCP	Eutrophication	Eco-toxicity	Human toxicity
	(gSO_2eq/MWh)	(gC_2H_4eq/MWhe)	(gPO_4eq/MWhe)	(g1,4-DCBeq/MWhe)	(g1,4-DCBeq/MWhe)
Mining	33.551	2.914	3.317	761.117	1463.489
Conversion	1.002	0.165	0.164	0.226	1.493
Enrichment	1.395	0.061	1.018	0.252	1.587
UOX fabrication	0.053	0.002	0.017	0.000	0.071
Reactors	2.887	0.151	0.760	0.005	4.331
Disposal	0.253	0.023	0.031	0.000	0.313
Total	**39.15**	**3.32**	**5.31**	**761.60**	**1471.29**

(0.65 gPO_4^{3-}eq/MWh_e). Reprocessing only accounts for 2% of the land use whereas the front-end accounts for more than 70%. Consequently, land use is higher for the once-through fuel cycle. Water withdrawal (as well as consumption) is mainly driven by reactor operation, therefore little change is expected and calculated.

Table 7
NELCAS results for the radioactive impact indicators for the OTC..

	Radioactive gaseous emissions	Radioactive liquid emissions	Radioactive solid waste			
			VLLW	ILW-SL	ILW-LL	HLW
	(Bq/kWhe)	(Bq/kWhe)	(m^3/TWhe)	(m^3/TWhe)	(m^3/TWhe)	(m^3/TWhe)
Mining	797,352		3815			
Conversion	2,E-04	60	2.15	1.29		
Enrichment	6,E-05					
UOX fabrication	2,E-05					
Reactors	162	2717	22.95	24.61	0.32	1.17
Total	**797,514**	**2777**	**3840**	**25.90**	**0.32**	**1.17**

Indicators dealing with radioactivity have a quite different behaviour. First, the gaseous emissions are strongly reduced in the once-through fuel cycle. Actually, the noble gases (mainly coming from the reprocessing step) which represent 45% of the gaseous releases in the TTC are not released in the OTC. Only the radon coming from the mining is still released in the OTC. The radioactive liquid wastes are also reduced in the OTC since the 90% of the tritium coming from the reprocessing does not show in the OTC. For the solid radioactive waste, the amount of VLLW is higher in the OTC since 99% of them come from the mining. The situation is different for the ILL-SL and ILL-LL. As they are produced in the reprocessing step, a lower amount is expected in the OTC. Finally, as all the spent fuel is considered as a waste in the OTC, hence, HLW inventory is three times higher in the OTC.

This has a very strong impact on the repository excavated volume and surface area. Actually, the excavated volume per spent fuel assembly (HLW) varies from 94 to 111 m^3 depending on the type of spent fuel. Knowing that about 2400 assemblies are discharged every year, it corresponds to a required excavated volume of about 590 m^3/TWh_e. This has to be compared with 830 canisters of HLW glass produced yearly in the TTC, corresponding to only 111 m^3/TWh_e (55 m^3/canister). On the opposite, only 7 m^3/TWh_e are needed for the ILW-LL in the OTC compared with 34 m^3/TWh_e in the case of the TTC. Therefore, even if the total volumes of the waste to be disposed of are almost the same in OTC and TCC (1.49 m^3/TWh_e for the OTC compared with 1.53 m^3/TWe for the TTC), the repository volume for the OTC is about 3.4 times higher than the one of the TTC (597 vs. 145 m^3/TWh_e). This is explained by the fact that the HLW volume represents only 24% of the waste to be disposed of in the TTC whereas it represents 78% in the case of the OTC (Fig. 9).

Moreover, as the HLW wastes represent 96% of the total waste radioactivity, decreasing their inventory has a significant and positive influence on the ultimate waste long-term toxicity. The relative radiotoxicity of HLW produced by the close fuel cycle is only 4% of the relative radiotoxicity of the HLW from the open fuel cycle. Consequently, the burden of the radioactive waste management to

the future generation is reduced by two orders of magnitude (Fig. 10).

In addition, the reprocessing also allows the radioactive nuclides to be trapped in an efficient waste form: the R7T7 nuclear glass, the lifetime of which has been demonstrated to be higher than 300 ky [61]. The nuclear glass also allows a significant reduction of repository impact due to the absence of the so-called IRF (instant released fraction) as in spent nuclear fuel. Indeed, IRF leads to the early release of highly mobile radionuclides as ^{129}I or ^{36}Cl, which significantly contributes to the long-term impact of the geological repository [62].

Furthermore, as the OTC requires a higher amount of natural uranium (17%) to produce the same amount of electricity, the natural resource efficiency is lower for the OTC (53.4 GWh_e/tU_{nat} for the TTC vs. 44.6 GWh_e/tU_{nat} for the OTC).

6. Conclusion

This study aimed at establishing a life cycle analysis of the current French twice-through nuclear fuel cycle and of an equivalent once-through nuclear fuel cycle and to compare their respective environmental impact. In principle data from 2010 were used as reference. When not available, data from year 2007, 2008 or 2009 were used instead and/or data were extrapolated from similar systems using the CEA scenario evaluation expertise.

The LCAs were limited to the first order contributors from accurate and reliable data on all the steps and facilities on the fuel cycle. However, the results obtained on the selected indicators are in accordance with data published in the literature on foreign or model fuel cycles. It emphasized that the nuclear energy in the French current scenario is one of the less impacting energy. In general the French nuclear energy generation compares relatively well with other energy sources in terms of sustainability impacts. As expected atmospheric pollution and greenhouse gas generation have lower impact than in many other sources and at the level of hydropower. Land use and water use and withdrawal compare disfavourably with other energy sources, while nuclear waste management remains the key critical impact of the overall nuclear cycle.

In this context, the comparison of the French scenario with an once-through fuel cycle scenario leading to the same energy production with the same nuclear facilities from the mining to the repository demonstrates that an OTC would have a larger environmental footprint on the “non-radioactive indicators” and would produce a larger volume of high level radioactive waste (three times more HLW). More significant, for similar total ILW-LL and HLW volumes (1.49 compared to 1.53 m^3/TWh_e), the repository volume for the OTC is 3.4 times higher, dedicated at 99% to the disposal of the HLW. Repository impact is hence anticipated to be much higher in the once-through fuel cycle than in twice-through cycle.

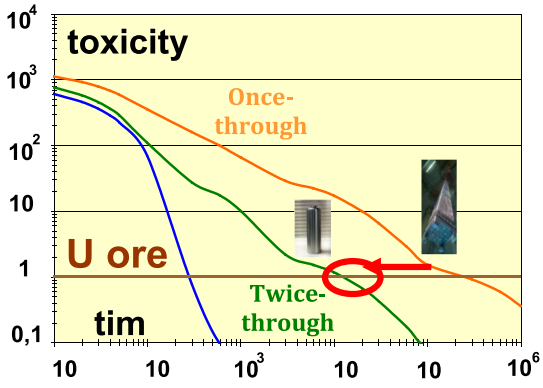

Fig. 10. Evolution of the relative radiotoxicity of the ultimate radioactive waste for the OTC (orange) and TTC (green). Apparent radiotoxicity of uranium ore was arbitrarily fixed at 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Only the radioactive releases (gaseous and liquid) are lower in the OTC because these releases mainly come from the reprocessing of the spent fuel in the TTC. However, this must be balanced by the fact that these annual releases represent less than 1% of the annual natural radioactivity.

In conclusion, this study demonstrates that the current French twice-through fuel cycle has a lower environmental footprint than an equivalent once-through fuel cycle, allowing more than 17% saving of the natural uranium resource and leading to a significant saving of the underground repository which is also a scarce resource to preserve.

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