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ARTICLE

Comparison of the Environmental Balances of Different Nuclear Power Cycles

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The French National Plan for the Management of Radioactive Materials and Waste (PNGMDR) 2022-2026 asks CEA and the industrialists to assess the environmental impacts of different spent fuel reprocessing options for evolving nuclear reactor fleets. Within the new starting fleet, comprising 1650 MW EPR2 reactors, three options have been considered. A life-cycle assessment (LCA) has been performed through a model using GaBi™ software, enabling to determine the most impacting factors along the different stages of the nuclear cycles.

Keywords: life cycle assessment (LCA), environmental impact, EPR2, fuel cycle, plutonium and reprocessed uranium recycling

I. Introduction

Many papers have been published about the LCA of nuclear electricity, resulting in very scattered values of indicators,[1-3] among which Global Warming Potential (GWP) is the most widely analysed.[4-9] This can be explained by a long cycle, with many processes and parameters that can vary a lot depending on electric mixes of considered countries. As France owns all stages of the nuclear cycle, except uranium mines, and as the relative importance of the nuclear electricity within the energy transition is publicly discussed (between 0 and 50% in 2050), an LCA model has been developed in order to be able to compare different cycles with various fleets of reactors in terms of environmental footprint. This study has been ordered by the French authorities in the frame of the PNGMDR (National Program for radioactive waste management) to compare the environmental impacts between the present nuclear fleet (series of 900, 1300 and 1450 MWe) and the future one consisting in 1670 MWe. Very few studies[10,11] have been performed relative to EPR reactors in their nuclear cycle.

II. Assumptions for Modelling

A 3rd generation nuclear fleet has been considered in France, expected to start to be constructed by 2027, including a first series of 6 EPR2 reactors, which should be followed by 8 others and probably 10 others until 2060, totalising 24 reactors for a total power of 40 GWe, replacing the former 2nd generation of PWR reactors that supplied 63 GWe until 2020.

Three different cycles are considered in this 3rd generation:

- a so-called "open cycle" (officially named "one-through cycle"), considering the spent fuel as a waste, i.e. without reprocessing. This cycle needs 5782 t of natural U/year,
- a plutonium mono-recycling cycle, using only plutonium stemming from reprocessing to manufacture mixed oxide (MOX) fuels, which will be fed in 8 reactors. This cycle needs 5137 t of natural U/year.
- a plutonium and uranium mono-recycling cycle, allowing to recycle plutonium in 7 reactors fed with MOX fuel and reprocessed uranium (RepU) in 2 reactors fed with ERU fuel (which has been done between 1994 and 2013 in the French 900 MW reactors of Cruas). This cycle needs 4741 t of natural U/year.

The lifespan of facilities is 60 years for EPR2 reactors and the necessary plants of the cycles, except for the final repositories of wastes, considered to be operated during 100 years and after only supervision.

The complete inventories of the different plants of the cycle (mining, conversion, enrichment, ENU fuel fabrication, reactors, reprocessing, MOX fabrication, waste interim storage and final repositories) have been established for the year 2015 or 2016, with Orano and EDF's contributions.[4] Plant inventories have been drawn up for typical production in 2015 and 2016, and are entered in the operating sub-assembly of each plant's GaBi™ model. Each plant is defined by a plan containing the three phases of plant life: construction, operation and dismantling. For the construction and operation of front-end plants (from mining to fuel fabrication) and back-end plants (from reprocessing to storage of waste excluding MLW and HLW), the inventories are described in Ref. 12). For the construction of EPR2 reactors, the data come from CEA reactor experts. For reactor operation, inputs are taken from Ref. 4), while outputs are correlated from EDF public data.[13] Reactor water consumption is based on the assumptions described in EDF.[5]

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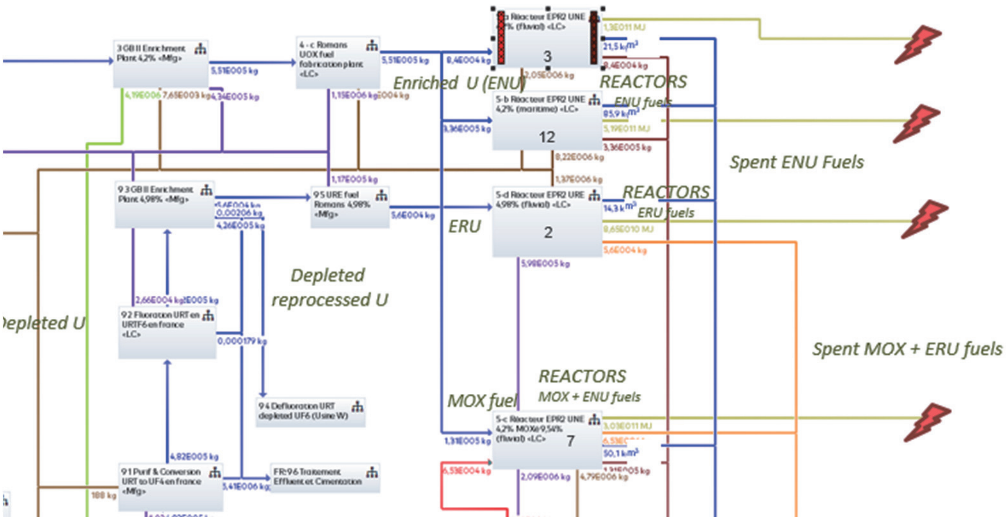

Fig. 1 Part of GaBi™ scheme in case of Pu + U monorecycling scenario

It has been assumed that half the fleet is located on the seafront and the other half along rivers with air cooler systems. Considering an optimistic load factor of 0.83 for this 3rd generation fleet, the amount of electricity production is considered to be 288 TWh/year.

In those inventories, we have focused on inputs (energy including electricity, diesel oil or gas, reagents, water, land use) and outputs (hazardous and non-hazardous wastes, radioactive solid wastes with their various categories, gaseous and liquid radioactive and chemical releases to the environment). For inventories of MLW (medium long-lived) and HLW (high level waste) waste storage, the data come from Andra.[12] For decommissioning, as no data is available at the present time, it was decided to use the same quantities of electricity and fuel oil as for construction, while waste volumes were taken from operators data and correlated to our CEA expert assessment.

In more details, three different types of uranium mines are considered: underground, open-pit and in-situ leaching, taking the inventories from mines and associated milling plants operated by Orano (Cominak and Somaïr in Niger, Katco in Kazakhstan, with uranium proportions of 54-18-28% respectively), the conversion is carried out in France within Malvesi (yellow cake to UF_4) and Pierrelatte (UF_4 to UF_6) plants, enrichment performed by GBII plant using ultracentrifugation. RepU is converted and enriched in facilities considered to be located in France, to manufacture enriched reprocessed uranium (ERU) fuels in the Romans facility of Framatome. As for the LCA study, the functional unit is the production of 1 MWh of nuclear electricity by reactors, without considering the distribution step. Modelling with GaBi™ software links each part of the process to enable the expected electricity production for the number of reactors defined above. As uranium requirements are linked to the quantity of electricity produced, the model adjusts the requirements of each plant. It is therefore possible to choose the type and number of reactors used in a model to determine the impact of recycling a nuclear material, whether plutonium or uranium.

Figure 1 presents part of our GaBi™ flow diagram. The EF 3.0 method[14] for impact assessment, recommended by the European Commission, has been favoured including 16 main and 12 secondary indicators covering all environmental areas, whereas alternative methods are sometimes resorted to for some other indicators than GWP.

III. Results and Discussion

LCA results are presented in different ways to open the discussion. **Table 1** shows the environmental impacts obtained with EF 3.0 on 16 categories, the sub-categories being not displayed.

Very small differences are observed between the cycles, despite a uranium saving of 10% from cycle 1 to 2 and another 10% from cycle 2 to 3. Note that in EF method, uranium is considered in the fossil resource category and not mineral and metals.

Figure 2 shows the contributions of the life cycle phases for the 16 main indicators of the EF 3.0 method. As mentioned above, the construction of all facilities is taken into account.

For some indicators, only construction is responsible for the impacts (human toxicity cancer), for some others only operation (ionising radiation, ozone depletion, water use); for the third kind, both construction and operation need to be taken into account to explain the impacts (GWP, ecotoxicity, eutrophication, resource use) as shown on **Table 2.** The same kind of breakdown should be explained for the construction part, but is not presented in this paper because this life cycle phase is much less contributing to most indicators except human toxicity cancer mainly due to stainless steel fabrication for reprocessing plant and reactors**. Figure 3** makes a focus on the Global Warming Potential indicator (GWP, also called Climate Change) and shows the contributions of the different steps of the nuclear cycle (only the three kinds of mines are separated to show the influence of each).

Beyond the 16 indicators of the EF method, whose are not at the same level of confidence,[14] we consider that a focus

Table 1 LCA results for 3 cycles with the future 40 GWe French EPR2 nuclear fleet

EF 3.0 Method	Open cycle (1)	Pu mono-recycling (2)	Pu + ERU mono-recycling (3)
Climate Change (kg CO2 eq.)	3.2	3.1	3.0
Acidification (Mole of H+ eq.)	2. 7E-02	2.5E-02	2.3E-02
Ecotoxicity, freshwater (CTUe)	7.6E+01	7.1E+01	6.4E+01
Eutrophication, freshwater (kg P eq.)	7.7E-06	7.7E-06	7.7E-06
Eutrophication, marine (kg N eq.)	6.1E-03	6.7E-03	6.4E-03
Eutrophication, terrestrial (Mole of N eq.)	5.1E-02	4.8E-02	4.5E-02
Human toxicity, cancer (CTUh)	7.8E-09	1.1E-08	1.0E-08
Human toxicity, non-cancer (CTUh)	3.5E-08	3.3E-08	3.2E-08
Ionising radiation, human health (kBq U235 eq.)	1.1E+03	1.4E+03	1,3E+03
Land Use (Pt)	9.9E+02	9.3E+02	8.7E+02
Ozone depletion (kg CFC-11 eq.)	7.6E-08	6.8E-08	6.2E-08
Particulate matter (Disease incidences)	1.8E-07	1.7E-07	1.6E-07
Photochemical ozone formation, human health (kg NMVOC eq.)	1.6E-02	1.5E-02	1.4E-02
Resource use, fossils (MJ)	9.1E+01	8.0E+01	8.1E+01
Resource use, mineral and metals (kg Sb eq.)	2.6E-06	2.8E-06	2.7E-06
Water use (m³ world equiv.)	8.4E+00	8.4E+00	8.4E+00

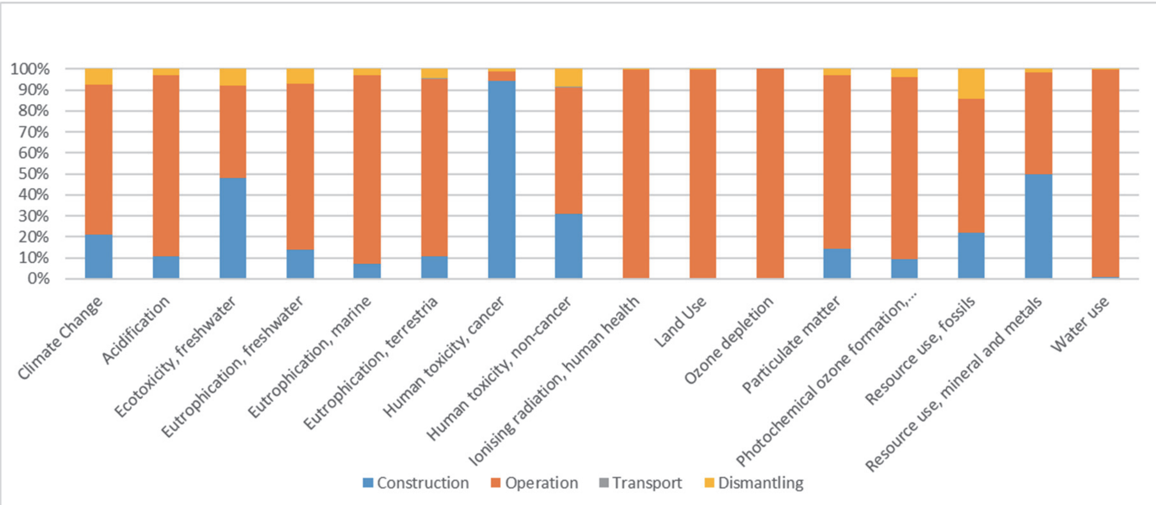

Fig. 2 Contributions of the life cycle phases of the monorecycling U + Pu cycle

should be made on the nuclear waste volumes, which are not covered by the "ionising radiation" indicator. Mine tailings, or to be more accurate, residues from milling, are stored on-site as huge heaps, except for the in-situ recovery which has the advantage of producing no residues. The global mine tailing volumes depend on the breakdown of mining techniques and the ore grade. The figures obtained here correspond to the 3 mines operated by Orano.

The partly closed cycles produce much less mine residues and MLW + HLW, the latter categories due to be stored in the deep repository center (Cigeo for France).

As LCA is a multicriteria method, one should comment other categories than climate change. We have chosen to address water use, which is a largely debated item of the nuclear industry, because of possible conflicts of use in the context of seasonal drought of some regions. The EF Water use indicator gives the global withdrawal of water (m^3 water eq of deprived water) of the studied system and is known to have the lowest level of robustness (III).[14] It takes into account not only the water used by the system, but also the impact of this water withdrawal on the surrounding environment.

Table 4 presents the unit withdrawals of the present EDF nuclear fleet, where three types of air-cooled heat exchangers exist.

If, as an assumption formerly explained, 12 reactors are

Table 2. Breakdown of the operation part of the different steps for the monorecycling Pu+U cycle

Monorecycling Pu + U	Mining & Milling	Conversion	Enrichment	UOX fuel fabrication	Reactors	Reprocessing and MOX fabrication	RepU cycle	Interim and final storages
Climate Change	61%	11%	1%	1%	6%	13%	1%	5%
Acidification	88%	3%	0%	1%	2%	5%	0%	1%
Ecotoxicity, freshwater	39%	4%	6%	1%	12%	18%	2%	18%
Eutrophication, freshwater	11%	3%	3%	1%	56%	16%	1%	9%
Eutrophication, marine	49%	2%	0%	0%	27%	19%	0%	1%
Eutrophication, terrestrial	81%	5%	0%	1%	5%	6%	1%	2%
Human toxicity, cancer	47%	5%	5%	2%	7%	18%	2%	15%
Human toxicity, non-cancer	54%	5%	3%	1%	7%	17%	1%	12%
Ionising radiation, human health	62%	0%	0%	0%	11%	27%	0%	0%
Land Use	71%	2%	1%	1%	20%	4%	0%	1%
Ozone depletion	100%	0%	0%	0%	0%	0%	0%	0%
Particulate matter	85%	4%	-1%	2%	2%	6%	0%	2%
Photochemical ozone formation, human health	85%	3%	0%	0%	4%	5%	0%	2%
Resource use, fossils	37%	6%	8%	2%	3%	19%	2%	23%
Resource use, mineral and metals	1%	1%	1%	82%	0%	10%	2%	2%
Water use	1%	0%	0%	0%	97%	1%	0%	1%

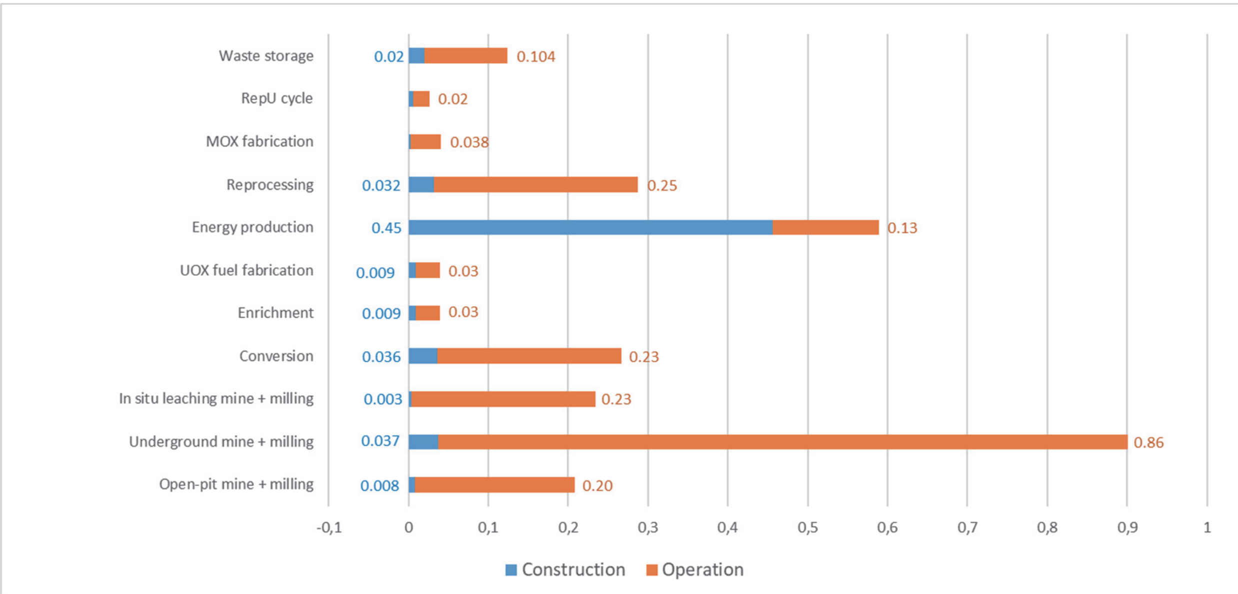

Fig. 3 Contributions of the life cycle phases of the monorecycling U + Pu cycle

Table 3 Volumes of raw, unpackaged nuclear wastes of the 3rd generation fleet (40 GWe)

m³/year/TWh	Open Cycle	Pu mono-recycling	U + Pu mono-recycling
Mine tailings	2 652	2 363	2 176
VLLW	38	40	39
LLW-SL	29	33	32
LLW-LL	1.8	1.8	1.7
MLW	0.7	1.6	1.5
HLW	2.3	0.7	0.9

VLLW: very low level waste, LLW: low level waste (SL: short-lived; LL: long-lived), MLW: medium long-lived, HLW: high level waste

Table 4 Water consumption of nuclear reactors[5)]

Cooling type	Water withdrawal (L/kWh)	Return rate of water
Open loop for seafront reactors	182	100%
Open loop for riverside reactors	169	99.8%
Closed loop for riverside reactors	10	77%

located along rivers with air cooling systems, consuming (withdrawal - discharge) indeed 2.3 m^3/MWh, we should find for the future fleet of 24 reactors about 1.15 m^3/MWh.

Moreover, we know that 97% of water use in all cycles is due to the cooling of reactors (Table 2).

Yet, EF 3.0 gives as a result for Water use a value of 8.4 m^3 world eq/MWh, which is far too much.

Therefore alternative methods have been tested within our GaBi™ model. The results are displayed in **Table 5**.

Analysis of the other water indicators available on the

Table 5 Results of water indicators for different methods (monorecycling Pu+U cycle)

Water consumption/MWh	Mines	Conversion	Enrichment	UOX fuel fabrication	Reactors	Reprocessing and MOX fuel fabrication	RepU cycle	Interim and final storages	Total
EF 3.0 Water use [m³ world equiv.]	0.06	0.01	0.03	0.02	8.03	0.09	0.01	0.04	8.28
AWARE 1.2C, global average for unspecified water [m³ world equiv.]	0.47	0.01	0.04	0.00	9.37	0.09	0.01	0.05	10.0
Blue water consumption [kg]	17.9	1.44	4.31	1.67	**1150**	5.42	0.82	5.23	**1187**
Blue water use [kg]	456	489	1183	1124	5009	2240	253	3300	14052
Total freshwater consumption, including rainwater [kg]	18.7	1.89	5.12	2.48	**1150**	7.43	1.09	7.62	**1194**
Total freshwater use [kg]	457	489	1183	1125	5009	2242	253	3302	14060

Table 6 LCA results for 3 cycles of the present 63 GWe French nuclear fleet

EF 3. Method	Open cycle (1)	Pu mono-recycling (2)	Pu + U mono-recycling (3)
Climate Change (kg CO2 eq.)	4.2	4.1	4.0
Acidification (Mole of H+ eq.)	3.2E-02	3.0 E-02	2.9 E-02
Ecotoxicity, freshwater (CTUe)	8.6E+01	8.2 E+01	8.2 E+01
Eutrophication, freshwater (kg P eq.)	9.7 E-06	9.7 E-06	9.7 E-06
Eutrophication, marine (kg N eq.)	9.0E-03	9.8 E-03	9.4 E-03
Eutrophication, terrestrial (Mole of N eq.)	6.3 E-02	5.9 E-02	5.7 E-02
Human toxicity, cancer (CTUh)	9.9 E-08	1.0 E-07	1.1 E-07
Human toxicity, non-cancer (CTUh)	4.4 E-08	4.3 E-08	4.3 E-08
Ionising radiation, human health (kBq U235 eq.)	1.3 E+03	1.7 E+03	1.6 E+03
Land Use (Pt)	1.3 E+03	1.2 E+03	11 E+03
Ozone depletion (kg CFC-11 eq.)	8.5 E-08	7.7 E-08	6.9 E-08
Particulate matter (Disease incidences)	2.2 E-07	2.1 E-07	2.1 E-07
Photochemical ozone formation, human health (kg NMVOC eq.)	1.9 E-02	1.8 E-02	1.7 E-02
Resource use, fossils (MJ)	1.1 E+02	1.0 E+02	1.0 E+02
Resource use, mineral and metals (kg Sb eq.)	9.7 E-06	1.2 E-05	1.0 E-05
Water use (m³ world equiv.)	9.1 E+00	9.2 E+00	9.0 E+00

GaBi™ software shows that 'Blue water consumption' and 'total freshwater consumption', including rainwater' indicators enable us to recover the value of the reactors announced by EDF, with the distribution of EPR2s considered. The results in Table 5 seem to indicate that the two above-mentioned indicators enable us to assess the gross impact of reactor water consumption, while the EF indicator seems to broaden the impact of this use on the surrounding environment, leading to a much more significant result than simple consumption.

IV. Comparison with the Present Nuclear Fleet

The present French nuclear fleet, called 2nd generation, was composed until 2020 of 34 reactors of 900 MW, 20 reactors of 1300 MW and 4 reactors of 1450 MW, providing with the best load factors (2015) 419 TWh of electricity. This fleet has been modelled in the same way as for the 3rd generation. The assumptions are the same, except for the lifetime, taken as 50 years, even if efforts are being made by EDF to extend it to 60 years. It seems important to compare the environmental impact of both fleets within a given cycle with a multi-criteria approach in order to make the future fleet of reactors eligible for the least polluting electricity production means.

The LCA impacts are presented in **Table 6**. In order to set up a thorough comparison, calculations have been made to bring closer 2nd and 3rd generation fleets, i.e. extend the 2nd generation to 60 years in lifetime and to reduce the load factor of the 3rd generation fleet to that of the 2nd one, i.e. Kp = 0.757. The results are presented hereafter in **Table 7**.

All parameters considered, the Gen3 fleet is around 20% more efficient than the Gen2 fleet, requiring less fuel per unit of electricity production. This corresponds to a slightly higher burn-up: 52 GWj/tHM (ton of heavy metals) versus 45 GWj/tHM for the current Gen2 fleet. Another comparison has been made for all other indicators between Gen2 and Gen3 nuclear fleets: considering the nominal results, relative differences between them vary from -89% for human toxicity cancer to +2% for ecotoxicity freshwater, 7 of them being larger than 30% which could be considered an uncertainty value above which values are taken as significantly different.

Table 7 Comparison of uranium need between present and future fleets

Fuel Type	Gen2 - 60 years Nuclear material need for the reactor fleet (t U/year)	Gen2 - 60 years Electricity production (TWh/year)	Gen2 - 60 years Nuclear material need for electricity production unit (t U/TWh)	Gen3 - Load factor 0.757 Nuclear material need for the reactor fleet (t U/year)	Gen3 - Load factor 0.757 Electricity production (TWh/year)	Gen3 - Load factor 0.757 Nuclear material need for electricity production unit (t U/TWh)	Ratio of uranium need Gen3 /Gen2
	Open cycle						
ENU	1201	420	2.86	612	262	2.34	0.82
	Pu mono-recycling						
ENU	1071	376	2.85	544	233	2.34	0.82
MOX	130	43	2.99	68	29	2.34	0.78
	Pu+U mono-recycling						
ENU	962	338	2.84	502	214	2.34	0.82
MOX	119	40	2.99	60	25	2.34	0.78
ERU	120	42	2.88	51	22	2.34	0.81

However slight differences of an indicator within a model with the same inventories between Gen2 and Gen3, or between the three different cycles for one given fleet, highlights tendencies of higher or lower environmental impacts that can be explained by small inventories differences.

V. Conclusion

A model of the French nuclear cycle clearly confirms that nuclear power is a very low-carbon means of production, destined to play a key role in the energy transition alongside renewable energies.

The study shows that uranium mining plays a key role in a number of environmental impact indicators, such as greenhouse gas emissions, particulate matter and ozone depletion. The study also suggests that nuclear material recycling could play a positive role in reducing the impact of extraction by reducing the need for raw materials.

The progressive evolution towards more closed nuclear cycles will enable to reduce different categories of impacts, as long as the recycling processes (back-end operations) do not offset the gains made on front-end operations, due to a lower need of natural uranium, together with limited radioactive waste amounts. Therefore further R&D efforts need to be achieved, combined with detailed LCA studies.

VI. Perspectives

Some parts of the cycles are still missing and some more assumptions have been made, taking proxies: the zirconium sector is incomplete and an analogy with chromium fabrication has been done, the decommissioning of all facilities is considered with the same amount of energy (mixture of electricity and diesel oil) than construction, and the future storage facility for low activity-long lived (LLW) nuclides is not taken into account. Further work is planned to include these parts.

Some other tasks are in progress, such as carrying a comprehensive sensitivity study about the different possibilities of the front-end (which kind of mine, conversion and enrichment with which electricity mix…), which have obviously a significant impact on LCA results. Concerning the assessment of uncertainties, GaBi™ software from SPHERA proposes for uncertainty studies Data Quality Rating[14] and Data Analyst tool which need to be further developed, according to the authors.

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