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ARTICLE

Assessment of RepU Recycling Contribution to ESG Performance in French Nuclear Power Plant with a LCA "Pilot Study"

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Although nuclear energy is acknowledged for its low CO_2 emission, the fuel cycle front-end footprint can be further decreased through the use of recycled nuclear material resulting from spent fuel reprocessing. This paper presents a typical case of footprint reduction obtained with the use of Reprocessed Uranium (RepU) in Cruas French Nuclear Power Plant. The demonstration is based on a Life Cycle Assessment (LCA) screening study, also called "pilot study" in the paper, realized following LCA general method with Simapro© LCA software and ecoinvent 3.6 Database. Its main result is a significant decrease of climate change indicator (around 40%) compared to the 2022 EDF nuclear kWh LCA study. The calculation was extended by integrating two other LCA indicators, "particle matter/respiratory inorganics" and "resource depletion", for exploratory purposes. This pilot study will be improved as new data become available, with the purpose to lead to a standardized LCA study. It will also be a tool to identify and to quantify ways to further reduce RepU fuel cycle environmental footprint.

KEYWORDS: Reprocessed Uranium, fuel cycle, climate change, LCA, conversion, enrichment, transportation

I. Introduction

In ESG (Environmental, Social and Governance) performance assessments, it is widely acknowledged that nuclear energy has a low CO_2 emissions.[1)] Yet, a significant proportion of these emissions come from the front-end of the fuel cycle and can be further decreased through using recycled nuclear material resulting from spent fuel reprocessing.[2)] This paper presents a typical case of footprint reduction at the scale of one reactor obtained with the use of Reprocessed Uranium in EDF Cruas French Nuclear Power Plant.

In France, the fuel fabricated with Enriched Natural Uranium (ENU) is reprocessed at the Orano plant in La Hague after its irradiation in reactor. During this reprocessing step, final wastes (fission products, minor actinides and activated fuel structures) are separated from reusable nuclear materials (plutonium and uranium). The plutonium produced during irradiation is recycled to produce MOX fuel, and the Reprocessed Uranium (RepU), *i.e.* the recovered uranium containing "unburnt" ^{235}U, is re-enriched to produce Enriched Reprocessed Uranium (ERU) fuels. With the recycling of plutonium, EDF saves 10% of uranium supply and an additional 10% to 15% can be saved through the use of the RepU.

Between 1993 and 2013, ERU fuel assemblies were loaded in the four Cruas 900 MWe nuclear reactors and they produced nuclear energy with the same operating performance as standard ENU fuel assemblies. At the beginning of 2024, Cruas 2 reactor restarted operations with a full reload of ERU and the other Cruas reactors are gradually being supplied with ERU. EDF's objective is also to use ERU fuel in 1,300 MWe units of the French fleet starting from 2027, after obtaining the approval from French Nuclear Safety Authority. Thus, EDF aims at generating up to 15 GWe from ERU fuel in the coming decade.

Beside saving natural uranium, the use of RepU brings also benefits to sovereignty, as the RepU stored in France at the end of 2023 is equivalent to roughly 3 years of strategic uranium stockpile at the current level of energy consumption. The use of RepU also enables the reduction of the volume of final high-level waste by a factor of 4, compared to an open cycle where all spent fuel is considered as final high-level waste. It is also economically attractive as there is no expensive mining stage, although other front-end stages are more expensive when dealing with RepU as the decay chain of some even uranium includes short-lived energy gamma emitters that require special care for the nuclear material handling.

This paper focuses on environmental criteria through a Life Cycle Analysis (LCA) screening study. The LCA method is today the reference method for the multi-criteria environmental assessment of products or services. It is standardized (ISO 14040-44) and it is widely used by manufacturers and public authorities. The way the LCA is applied to screening study called "pilot study" in the paper is described in part II and the Environmental footprint results are given in part III.

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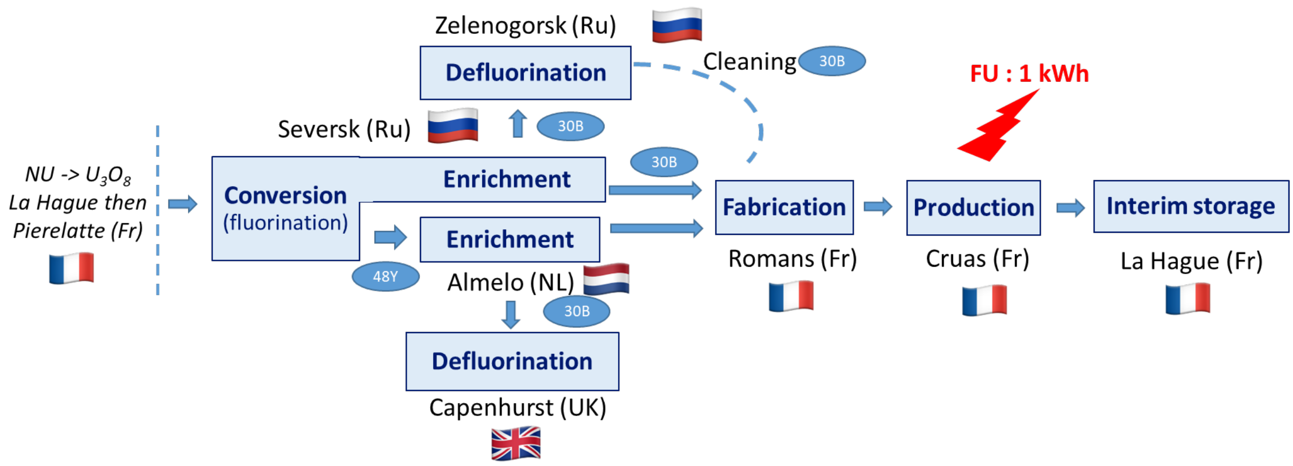

Fig. 1 Modelling layout for the pilot study

II. Method

The demonstration presented in the paper is based on a LCA "pilot study". Since RepU supply is re-starting in 2024 and consolidated information is not available yet, some data are based on preliminary experts' estimations. This is the reason why the present work is called a "pilot study", with the purpose of identifying the key parameters of RepU supply chain. Results will be improved as new data become available, with the objective of developing a full standardized LCA study.

The pilot study follows the LCA general method and was performed with Simapro© LCA software and ecoinvent 3.6 Database. Specific data for the RepU operations were provided by EDF Nuclear Fuel Division based on information collected from its suppliers. The other data come from 2022 EDF nuclear kWh LCA study.[3)] In this former study, used fuel reprocessing and Pu mono-recycling in MOX fuels were considered but RepU recycling was not.

In the current study, the reference flow associated to the functional unit is defined as **"1 kWh electrical energy produced by one Cruas reactor loaded with ERU fuels."**

The steps of the RepU fuel cycle that are considered in the study are (see **Fig. 1**):

- front-end steps: conversion, enrichment, fuel fabrication. RepU is obtained by the reprocessing of used Enriched Natural Uranium fuels, so there is no front-end step before RepU conversion in this "pilot study", otherwise this step will be counted twice within a dedicated ENU fuels LCA;
- electrical energy production step;
- back-end steps: fuel transportation and storage. Although ERU spent fuel could be reprocessed and the resulting RepU2 recycled (see for instance[4)]), ERU reprocessing is not considered in the study.

At every step, LCA method considers the environmental footprint of construction, exploitation and decommissioning of the fuel facilities and nuclear reactor. Three LCA impact category indicators (called "indicators" in the following) were selected for the study. **"Climate change"** in kg CO_2 eq unit was selected as it is the most important and robust indicator for assessing environmental footprint. The analysis of the results of this indicator will therefore be considered as the most relevant. In addition, the following indicators were selected to complete the climate change indicator and identify additional levers for improvement.

- **"Particle matter/respiratory inorganics"**, LCA indicator that accounts for the effects on human health of emissions of Particulate Matter (PM) and their precursors (NOx, SOx, NH3). This level 1 indicator according to International reference Life Cycle Data system, ILCD,[5)] expressed in kg PM2.5 eq, will enable to strengthen our analysis of the impact of the many transport stages in the RepU supply chain.
- **"Resource depletion"**, LCA indicator of the depletion of natural non-fossil resources. This level 2 indicator according to ILCD,[5)] expressed in kg Sb eq, is significant for the study as RepU supply reduces natural resource needs.

III. Environmental Footprint Results

1. Climate Change

The results for "Climate change" indicator of the pilot study and 2022 EDF nuclear kWh LCA study[3)] are shown in **Table 1**. There is a significant decrease of the climate change indicator (around 40%) compared to the previous EDF study[3)] that was achieved with the same tools and the same methods but did not consider RepU recycling.

Table 1 Result for "Climate change" indicator for 1 kWh produced in Cruas NPP with ERU fuel

Indicator	Result of this pilot study	*Result of 2022 EDF LCA[3)]*
Level 1 Climate Change (kg CO_2 eq)	**$2.3\ 10^{-3}$**	*$3.7\ 10^{-3}$*

The breakdown of the climate change indicator at each step is given in **Fig. 2**. The main contributor to the climate change indicator is the reactor construction phase. It is followed by the enrichment and conversion steps, whose contributions are strongly related to the carbonized energy mix they are supplied with (the energy mix refers to the electricity supply of the country, "national mix", where the enrichment or conversion are performed). The transportation step is not visible in Fig. 2, as it contributes only to 1% of the climate change indicator. This is because a small amount of nuclear material is transported - although over long distances – with regard to the huge quantity of energy it allows to produce. These results are consistent with other recent studies on the French nuclear fleet with different fuel cycle options.[6,7]

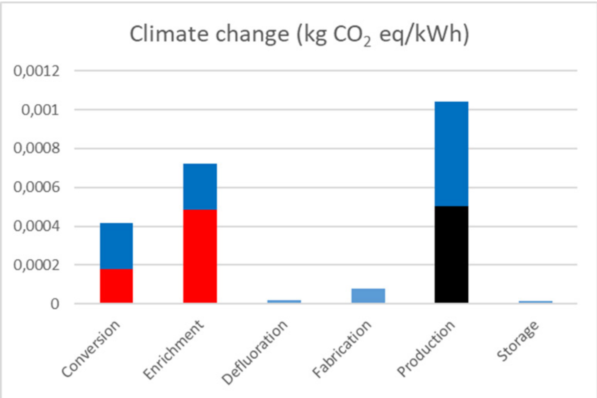

Fig. 2 Breakdown of each step for the climate change indicator, in black: contribution of construction phase, in red: contribution of electricity consumption, in blue: other contribution

To assess the overall variability of the results, a sensitivity study was conducted on four influential parameters of Climate Change indicator. Minimum and maximum values were provided by expert assessment, based on information collected from EDF suppliers (see **Table 2**).

Table 2 Parameters for sensitivity study

Step	Parameter	Reference value	*Min value*	*Max value*
Enrichment	Electricity (kWh/SWU)	35.5	*25*	*70*
Conversion	Electricity (kWh/kg UF_6)	11.4	*10*	*20*
Conversion	Heat (MJ/kg UF_6)	67.9	*55*	*85*
Conversion	Nitric Acid (kg/kg UF_6)	1.4	*1*	*2*

Results of the sensitivity study are shown in **Fig. 3**, the * indicates the result of the pilot study (2.3 10^{-3} $kgCO_2$ eq obtained with reference values of **Table 2**. The bars indicate the variation of the results as a function of the input parameters within min and max values given in Table 2. The last bar indicates the total variation within all min and max values of the parameters in Table 2. As it can be seen, the results are consistent, with an overall maximum variation of 30%. The energy mix of the electricity supply for the enrichment step is the parameter that carries the strongest impact on the results.

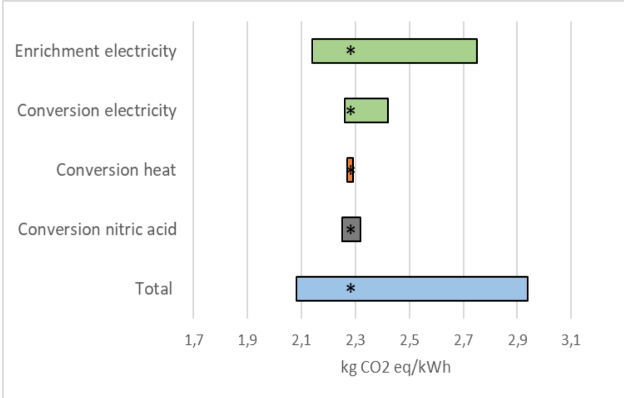

Fig. 3 Sensitivity study for Climate change indicator, * indicates the reference value.

2. Other Indicators

The results for **"Particle matter/respiratory inorganics"** and **"Resource depletion"** indicators of the pilot study compared to the 2022 EDF nuclear kWh LCA study[3] are shown in **Fig. 4**.

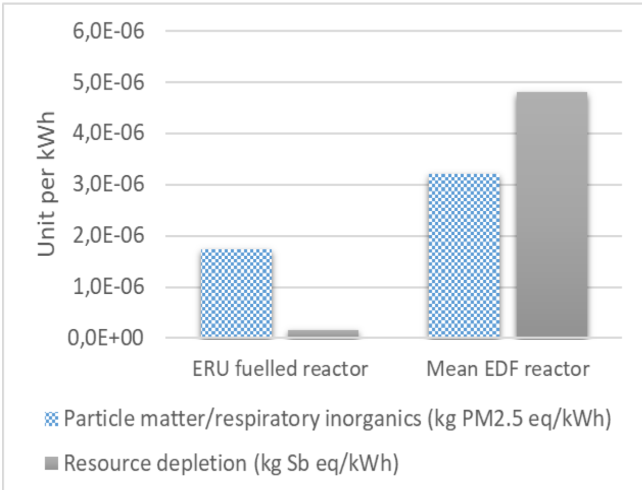

Fig. 4 Results for "Particle matter/respiratory inorganics" and "Resource depletion" indicators for 1 kWh produced in Cruas NPP with ERU fuel, compared to mean EDF reactor.[3]

The result for **"Particle matter/respiratory inorganics"** is 1.7 10^{-6} kg PM2.5 eq/kWh, showing a significant decrease (47%) compared to the previous EDF study.[3] The indicator is largely dominated by PM2.5 (66%), mainly resulting from the Russian energy mix. The SOX are produced by Russian electricity mix and material supply for the reactor (mainly nickel and copper). As for the climate change indicator, the main contributor steps are the reactor construction and the enrichment and conversion steps. A specific calculation showed that the transportation step contributes only to 0,9% of this indicator.

The result for **"Resource depletion"** is 1.6 10^{-7} kg Sb eq/kWh. There is a sharp decrease (97%) compared to 2022

EDF nuclear kWh LCA study[3)] where the result for this indicator was 4,8 10^{-6} kg Sb eq/kWh. This is due to the fact that Natural Uranium extraction step, not needed when RepU is used, is the overwhelming contributor to the indicator in EDF nuclear kWh LCA study[3)] (no consumption of uranium natural resource in RepU fuel cycle). The value of the indicator depends mainly on HydroFluoric consumption (46%) at the conversion step. It is important to notice that the benefit arising from HF recycling, which is implemented in France after the defluorination of the ENU, is not taken into account in this study, thus giving further robustness to our evaluation of the **"Resource depletion"** indicator.

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IV. Conclusion

This "pilot study" shows that recycling RepU can drastically reduce the carbon content of the electricity generated by a nuclear reactor and more broadly its environmental footprint since most of it generally originates from uranium extraction, not needed when enriched RepU is used to fuel reactors. The study also identified the key parameters of RepU supply chain in a LCA assessment and it can be considered as a first step towards a robust standardized LCA study.

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