Assessment of the anticipated improvement of the environmental footprint of future French nuclear energy systems

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Abstract. Environmental issues are nowadays a growing concern in the public opinion. It is therefore mandatory to propose relevant and qualified assessments of the overall environmental footprint of the different types of energy sources which are envisaged to be possibly implemented in future energy mixes. This question is particularly important for nuclear energy which suffers from a poor image in the public opinion due to the recent Fukushima accident. In this context, we developed a bespoke Life Cycle Assessment (LCA) tool, referred to as NELCAS, based on the current French nuclear energy system. Thanks to the Nuclear Safety and Transparency annual reports, detailed quantitative data are available for each of the fuel cycle facilities. The whole fuel cycle from ore-mining to geological repository was considered as well as data for construction, deconstruction of any plants, including the contribution of transports. All the matter and energy fluxes were considered and normalised versus the electric production. Key environmental indicators, such as land use, water withdrawal and consumption, gaseous releases, waste production … as well as potential impact indicators (acidification, eutrophication…) were hence assessed and validated with comparison with the few existing LCA results. This model was used to assess the respective figure of merits of the different generation of reactors and fuel cycles. In particular, it demonstrates that actinides recycling has a strong beneficial effect on the overall footprint due to the relative high impact of the front-end activities, specifically the ore mining. In the framework of a joint CEA-EDF-AREVA group, reference deployment scenario for the 4th generation reactors were developed for the French case based on both technical and economic considerations. The NELCAS tool was therefore used to assess the impact on the overall environmental footprint of this reference scenario.

Key Words: Recycling, environmental footprint, life cycle assessment, strategy, 4th generation reactors

1. Introduction

Nuclear energy is thought to be one of the energy sources that could help mitigating the global climate change together with the renewables, due to its low green-house-gases emissions, its reliability and its high load power. However, nuclear energy currently suffers from a poor image in the public opinion due to the successive Chernobyl and Fukushima accident, and the lack of industrial solution implemented for high level nuclear waste (HLW). Indeed, environmental issues are nowadays a growing concern within most of the public opinion in many countries. The subjective appreciation on the relative environmental benefit of a given technology play therefore an increasing role in the decision process in the society. In this context, developing reliable assessment of the overall environmental footprint of a given technology is a prerequisite before any political decision of deployment. This question is even more important for technologies which are not widely supported by a positive image, as nuclear energy. More generally, improving the environmental footprint has to be considered in the wider approach of the sustainability [2], which requires to simultaneously improve the durability, bearability and liveability. To meet the requirements of sustainability, an energy source has not only to be relevant in terms of technical efficiency and economics but has also to address simultaneously three main issues: (i) the energy transition towards low-carbon energy portfolios, (ii) the preservation of the Earth environment and climate of highly detrimental damages, and (iii) the promotion of social and societal stability, equity and democracy.

In this context, we developed in a previous paper a bespoke dedicated quantitative model, referred to as NELCAS, to reliably assess the environmental footprint of different types of nuclear systems [1]. This model was used to assess the respective environmental footprint of the current once-through cycle (OTC, the so-called open fuel cycle in which spent nuclear fuel is considered as an ultimate waste and has to be disposed deep underground) and twice-through cycle (TTC, the so-called closed fuel cycle in which uranium and plutonium from spent nuclear fuel are recycled respectively in URE and MOX fuels). This study demonstrated the very positive impact of the recycling implementation due to the relative high impact of fuel cycle front-end activities, in particular the mining activities. For the future, nuclear energy is supposed to involve 4th generation systems which are basically based on fast neutrons reactors (FNR). Assessing the anticipated environmental footprint of fast neutrons reactors fuel cycles is therefore of prime interest. In order to bring insights on this issue, NELCAS was used to assess the environmental footprint of FNR in the associated fuel cycles. First results are presented in this paper.

2. The NELCAS model, a relevant tool to assess environmental footprint of nuclear energy systems

Environmental footprint has to be assessed in a global approach, i.e. estimated by Life Cycle Assessment (LCA) approaches in order to consider not only the instantaneous production but also the whole life cycle, in particular the construction, operation, end-of-life cleaning and dismantling of the different facilities. Such general environmental footprint can be depicted thanks to a complete set of environmental indicators describing the influence of the process on the environment, due either to the withdrawal or to the release operations. The NELCAS model was developed to overcome the lack of LCA model and data in the literature for nuclear energy systems.

2.1. The NELCAS model and the environmental indicators

The relevance of a LCA model is mainly related to the reliability, consistency and completeness of the database used. One of the originality of the NELCAS model is to be based on a consistent set of actual data that have been extracted from the yearly environmental and safety report produced (the so-called TSN report) by any nuclear facility in France under the requirement of the Nuclear Safety and Transparency Law of 2006. It is hence based on the French situation as a representative situation and considers the whole fuel cycle, from the ore mining to the geological disposal, through the conversion, the enrichment, the fuel fabrication, the electricity production within the reactors, the fuel storage, the fuel recycling and the different types of waste conditioning plant and interim storages. Ultimate repository planned to be built in France by 2025 is also included. Non-reprocessed spent fuels are not considered as waste since they are planned to undergo a delayed recycling to feed 4th generation reactors. Eight key generic environmental indicators have been selected based on their frequency in literature (>25% of the literature) and their technical relevance: GHG emissions (mass of CO_{2eq}, g per kW electrical power), the atmospheric pollution (mass of SOx and NOx, mg per kW electrical power), the water pollution (mass of pollutants, mg per kW electrical power), the land-use (surface area, m^2 per GW electrical power), the water consumption (water is not released to the environment) and withdrawal (water is released after cooling) (volume of water, L per MW electrical power), and the production of technological waste (mass of waste, g per MW electrical power). Three indicators were selected addressing the radioactivity specificity: radioactive gaseous and liquid releases (activity, Bq per kW electrical power) and the solid radioactive waste production (mass or volume of waste, g per MW electrical power, or m^3 per MW electrical power). Five additional potential impact indicators have also been assessed: acidification, eutrophication, photochemical ozone creation potential (POCP), eco-toxicity and human-toxicity. By definition, they refer to a potential maximum impact that such release could generate and represent boundary overestimation.

2.2 The adaptation of NELCAS to the 4th generation nuclear energy systems.

In order to estimate the potential environmental footprint of 4th generation fuel cycles, NELCAS model was adapted and its database expanded towards FNR. In a theoretical pure FNR fuel cycle, a stable plutonium mass balance is achieved thanks to the multi-recycling of plutonium in MOx fuel and the intrinsic characteristics of FNR which allows us to transform fertile ^{238}U in fissile ^{239}Pu: the mass of plutonium which is yearly introduced as fuel in the reactor is identical to those at the outlet of the reprocessing plant. In such a fuel cycle, the nuclear fuel-cycle front-end operations are not needed and disappeared. We consider as FNR a Sodium Fast neutrons Reactors (SFR) feeded by MOx fuels which are manufactured from recycled Pu and from either reprocessed or depleted uranium, this latter being quite abundant in France due to the operation of the 2nd and 3rd generation reactors (the total stockpile is estimated to be around 435,000 t in 2035, ANDRA). The representative fluxes are shown in Figure 2.

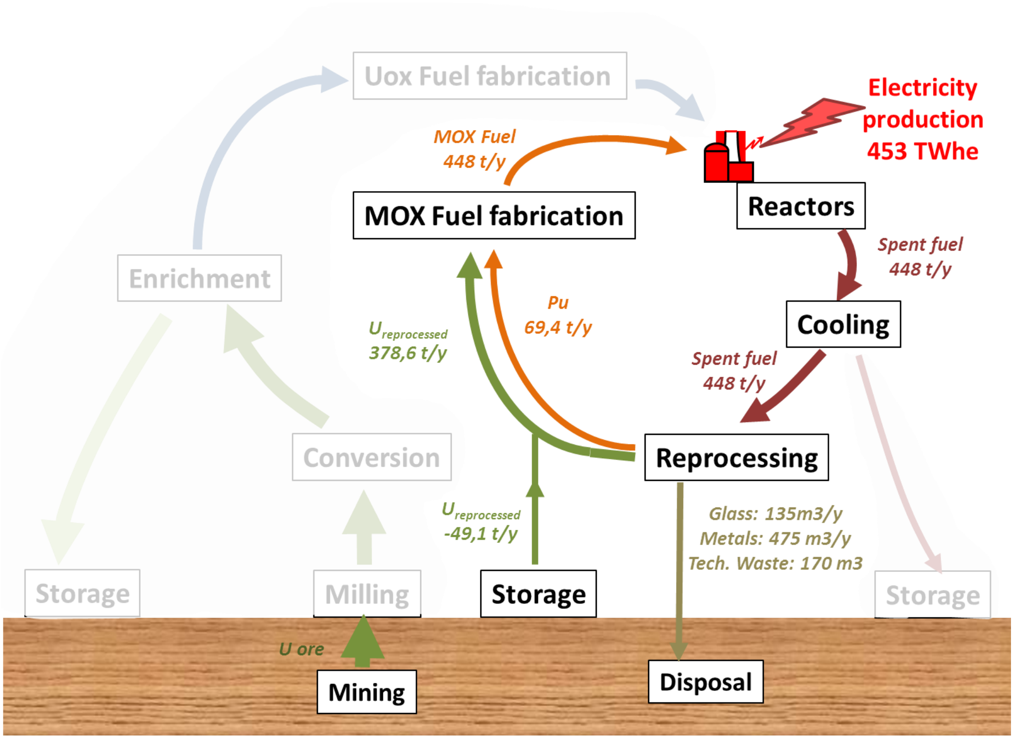

Figure 2: fuel cycle for the 100% SFR case study and its representative streams [3]

The SFR reactor considered in this paper has the following characteristics:

- an electrical production capacity of 1450 MWe,
- achieves 40% thermal efficiency with an availability of 85%,
- MOx containing 15.5% of plutonium is used to feed the reactor and the average fuel burn-up is increased to 100 GWd/tU,
- The lifetime of the reactor is anticipated to be 60 years (conception lifetime).

To be consistent with the previous assessment, we assumed the overall nuclear electricity production in France to be comparable to the reference current fuel cycle, close to 453 TWhe/y. The anticipated reactor fleet is therefore composed of 42 FNR which have to be fed with 448 t of MOx fuel manufactured from ~50t of reprocessed or depleted uranium taken from the French stockpile. For the SFR data, data were extrapolated from the available data existing for the Phenix and Superphenix reactors (TSN reports), taking into account an improvement factor since these were experimental reactor [3]. For the nuclear fuel cycles facilities (fuel fabrication and recycling plants, geological repository), we consider the current French facilities as in [1] and without any improvement, which is a very conservative approach.

3. The anticipated environmental footprint of SFR nuclear fuel cycles.

The calculated environmental footprint of SFR compared to TTC is presented in Fig.2 and Fig.3 presents the contribution of the various fuel cycle steps.

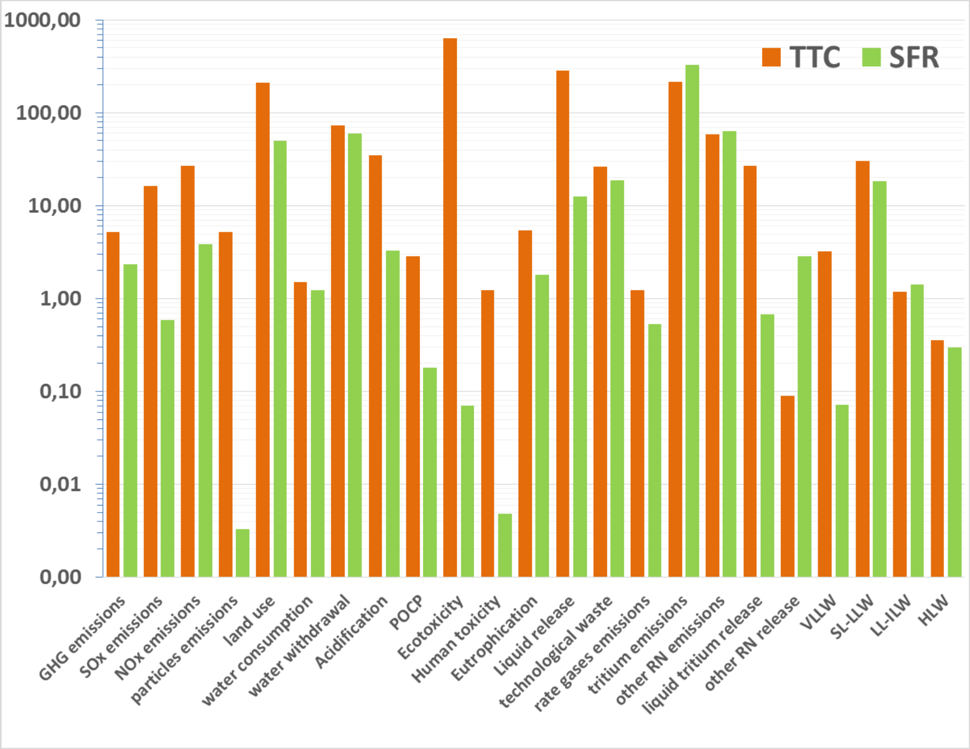

Fig.2: respective environmental indicators for the current TTC (mono-recycling of Pu as MOX fuels in current 2nd generation LWR) and SFR (multi-recycling of Pu in MOX fuels in Sodium Fast neutrons Reactors).

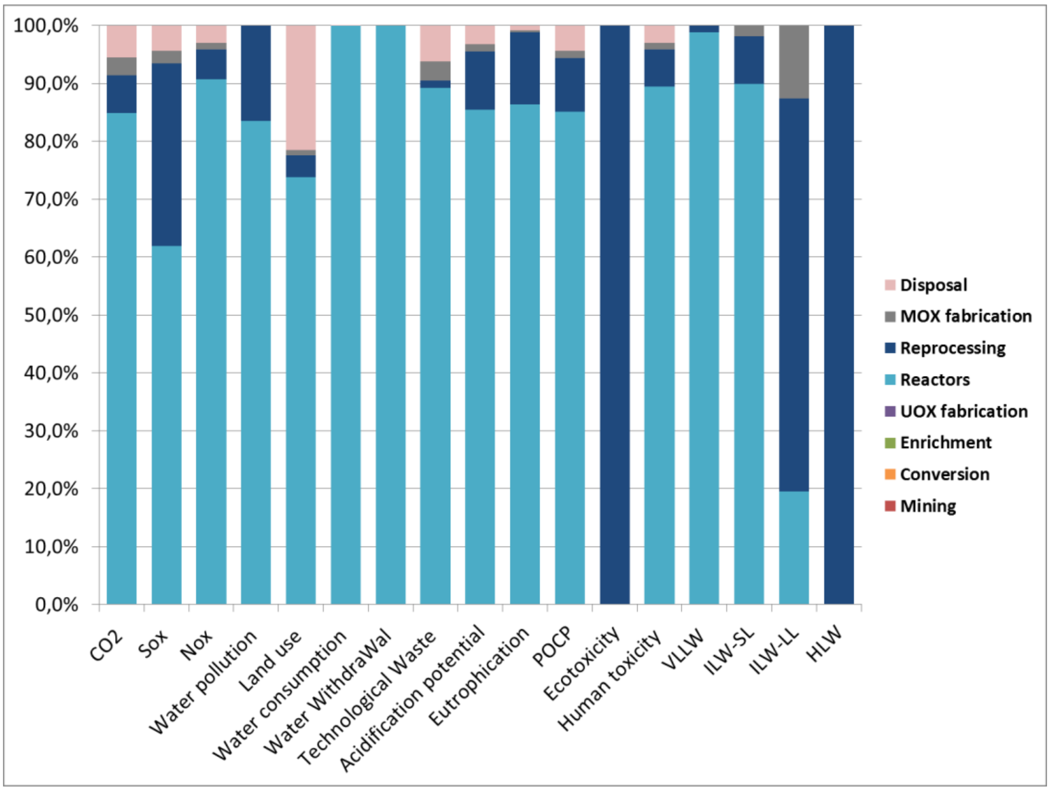

Fig.3: Relative contribution of each step of the fuel cycle to the environmental and technological impact indicators for the SFR scenario [3]

These results clearly show first that most of the indicators are much lower for SFR fuel cycles than for TTC with current LWR reactors, the only exceptions being the long-lived intermediate level waste and the other RN release. Such a beneficial situation for SFR nuclear fuel cycles is linked to several reasons:

- TTC indicators are dominated for most of them by the front-end activities, especially the mining, the only exception being the water withdrawal and consumption (used for the thermal cooling). By comparison, the back-end activities have a very limited impact. As a consequence, when front-end activities are replaced by back-end recycling activities, the overall environmental footprint is significantly improved. In pure SFR fuel cycle as the one modeled here, fuels are supposed to be fully manufactured from recycled plutonium and depleted uranium for which nuclear countries have very large stockpile (tailings from the enrichment step). No mining, neither conversion nor enrichment are therefore required for SFR fuel cycles.
- SFR fuel cycles are more efficient in the energy production and use more concentrated fuels. For the same electrical production, the mass of fuels to be fed in the reactors is therefore much lower (a factor in the order of two), which also yield to reduce the impact of fuel cycles activities.

In such fuel cycle, environmental footprint is hence dominated by the operation of the reactors as evidenced by Fig.3. It is noteworthy to remark that back-end activities have in most cases a very limited impact and a little contribution to the overall impact.

Regarding the specific radioactive release, the radioactive gaseous emissions represent nearly 99.9% of the total radioactive emissions which is similar to current fuel cycles. The absence of any mining operation in SFR removes the large contribution of radon. The radioactive gaseous emissions are therefore mainly coming from rare gases emitted during the SNF dissolution in the reprocessing plant. The radioactive release at a potential SFR reprocessing plant is expected to be significantly lower than for LWR reprocessing. Indeed, LWR reprocessing release significant amount of tritium which is initially trapped in irradiated Zircaloy cladding. In SFR 99% of tritium migrates to the sodium coolant during the reactor operation where it is further trapped as sodium hydrides by a range of traps (metallic frits, liquid nitrogen cooled activated charcoal traps…). Beyond tritium, the main contributors are mainly ^{54}Mn produced by the activation of the SFR core materials, and ^{14}C and ^{129}I which represents 18% and 7% of the liquid radioactive releases respectively.

4. Conclusion

NELCAS LCA model has been upgraded for assessing the overall environmental footprint of 4th generation nuclear fuel cycle based on SFR, based on the data available in France regarding the operations of the PHENIX and SUPERPHENIX reactors. It demonstrates the overall improvement that SFR could bring to the overall environmental footprint of energy. This improvement is not directly related to the respective merit of SFR by comparison to current LWR reactors but rather to the replacement of most of the front-end activities which have large impact factors by recycling activities, the impact of which is much lower. It confirms that enhancing the recycling activities in any fuel cycle has a very positive impact on the overall environmental footprint of nuclear energy systems as evidenced by the following figures:

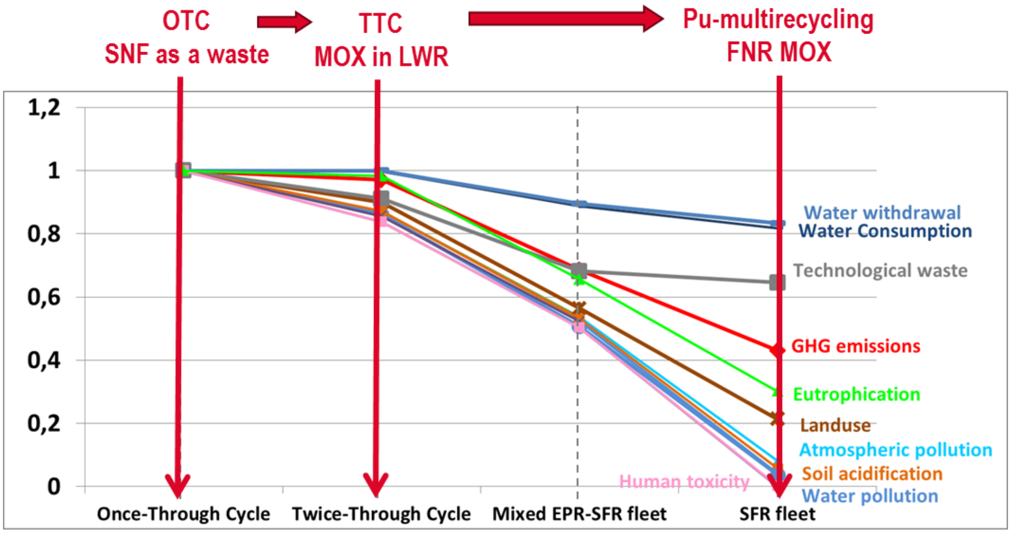

Fig. 4: Relative evolution of some key environmental indicators with increasing recycling options. Open fuel cycle (Once-through Cycle) is taken as a reference. Twice-through cycle (i.e. Pu and U mono-recycling, respectively in MOX and re-enriched reprocessed uranium fuels) is the present scenario in France [2].

These results also show that SFR environmental footprint is dominated by the reactors contribution, both construction/deconstruction and operation. Such a result should therefore urge the research and engineering teams to integrate the environmental dimensions in the design study of the future 4th generation SFR. Any improvement on the design of the reactor will have a very direct and visible effect on the overall footprint. Reversely, SFR design will be significantly questioned not only in terms of safety and performances, but also in terms of environmental footprint. Eco-conception approach should be a key driver for the future and would likely yield to significant improvement in the reactor designs.

References

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