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Improving the nuclear energy sustainability by decreasing its environmental footprint. Guidelines from life cycle assessment simulations

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ABSTRACT

This paper describes the anticipated long-term evolutions of nuclear fuel cycles. The main driver for such an evolution is the need for improving the sustainability of global energy systems. Indeed, sustainability is becoming the international reference approach to reconciling the different fields of analysis, *i.e.* the technical performance, economic viability, environmental preservation and societal acceptance. While our societies have to face the issue of finding new energy models which help to mitigate climate change, global approaches are mandatory to select the relevant improvements for the different energy systems, including nuclear energy. In a first step, this paper focuses on the specific environmental footprint of nuclear energy and its position with regards the other energy sources. From this situation, this paper depicts the potential improvement to be studied in order to improve the overall environmental footprint.

1. Introduction

Recent projections made under the auspice of the United Nations anticipate the population to be in the range of 9.5 billion by the year 2050 before reaching 10–12 billion around 2100 and stabilizing (UNO, 2013). As human and economic development is clearly related to energy consumption, at least as long as it stands below a threshold around 4000 kW h per capita (Pasternark, 2000), this will clearly lead to a significant increase of the total world energy consumption. Every international study performed under the auspices of the United Nations, the International Agency for Energy, or the Organisation for Economic Cooperation and Development predict a primary energy consumption increase by roughly 50% by 2035, and an electricity consumption increase by 75–90% even in the case of a strong political shift towards the "green economy" (WEO, 2012). Significantly increasing the energy production is hence mandatory and represents the first pillar of the energetic challenge to be faced in the XXIst century.

On the other hand, the current and drastic global climate change has now been clearly recognized and at least partially related to human activities (IPCC, 2013). This influence is first of all related to the very large amount of green-house gases (GHG) which have been produced since the start of the industrial revolution in the XIXth century: the concentration of CO_2 increased from 275 ppm to nearly 400 ppm in less than 150 years, whereas it had remained stable over the previous 10 000 years. Similar pictures can be described for other GHG like CH_4 and NO_2. Simultaneously, the average surface temperature on Earth is estimated to have increased by nearly 1 °C on the same time scale whereas the sea level has increased by roughly 20 cm during the XXth century. Simulations performed under the auspices of the IPCC and reported in the 2013 report evidenced that this evolution will go on as long as the GHG emissions are not decreased. It could lead to a global surface temperature increase ranging from 2 to 6 °C, depending on the scenario of the GHG-emissions. Decreasing the GHG emissions is today a worldwide issue shared by every country, even though they do not all agree on the path to follow. Considering that current energy production, which is for more than 80% based on fossil fuel

List of abbreviations: FNR, Fast Neutron Reactor; GHG, Green House Gases; HLW, High Level Waste; ILW-LL, Intermediate Level Waste – Long Life; ILW-SL, Intermediate Level Waste – Short Life; MOX, mixed uranium/plutonium oxide fuel; OTC, Once Through Cycle; POCP, Photochemical ozone creation potential; TTC, Twice Through Cycle; UOX, uranium oxide fuel; VLLW, Very Low level Waste.

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burning, is responsible for a large part of the GHG emissions, energy revolution towards carbon free energy will lead to preventing any GHG increase, the so-called energy transition. This corresponds to the second pillar of the energetic challenge to be faced in the XXI[st] century.

In this early XXI[st] century, our societies have to face a global energy challenge which is meeting our tremendous energy need while mitigating the climate and preserving the environment. This challenge requires changing the current energy model to shift towards low-carbon energies, mainly renewables and nuclear energies. However, although renewables are in general much better accepted by public opinion, nuclear is severely questioned regarding its safety and ability to properly manage its waste. Social acceptance is hence another key criterion to consider for defining the future energy mix.

More generally, the global energy challenge will be successfully addressed at the world level if the three previous domains are considered altogether: implementing an energy transition towards low carbon energies, preserving the future environment and climate of the earth, and promoting the social acceptability, stability and equity. This approach is the so-called "sustainable development" as defined by the Brundtland's commission in 1987: "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" (UNO, 1987). To meet the requirements of sustainability, an energy source has, therefore, not only to be relevant in terms of technical efficiency and economics, but has also to have a low environmental footprint, to be generally accepted and to promote the development of balanced and peaceful relationships within a given society (acceptance), between the different countries (international relations) and between different generations (inter-generational equity). These three main domains are intimately linked and have to be solved altogether (Fig. 1).

In order to bring key insights to this general question, a life cycle assessment tool (NELCAS) was developed in a previous paper for assessing the environmental footprint of nuclear energy and quantify the specific influence of recycling operations (Poinssot et al., 2014). Based on this overall picture, this paper aims to identify what are the main guidelines and key issues for improving nuclear energy environmental footprint, and therefore its sustainability.

2. What about the potential nuclear energy environmental footprint?

Being environmental-friendly, as one of the three pillars of an

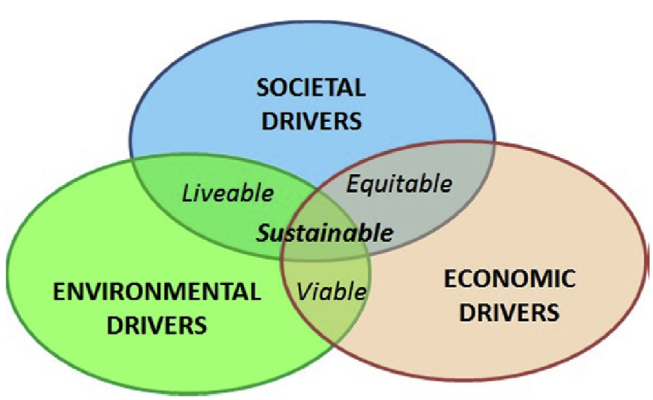

Fig. 1. The three main pillars of the sustainability, i.e. the ability to preserve the environmental, to promote the economic development and to develop balanced and peaceful relationships.

overall sustainability, has to be understood in a very general approach focusing on the following key issues:

- First, the energy sources have to limit or even mitigate the global climate change, which means yield to low GHG emissions;
- Second, it has to reasonably preserve the environment, which means the environmental footprint has also to be as low as possible. This relates in particular to the land-use requirement and the general emissions and withdrawal in the environment (in water, in the atmosphere …);
- Third, the scarce natural resource used to produce the energy has to be preserved for future generations and other uses, which means that one should aim to save it as much as possible by either promoting the highest overall efficiency in the scarce natural resource use, or by substituting it by other abundant materials thanks to innovative processes.

These very general objectives have to be assessed in a global approach, *i.e.* estimated by Life Cycle Assessment approaches in order to consider not only the instantaneous production but rather 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. Apart from GHG emissions, the environmental footprint of nuclear energy is very little documented in the scientific literature which concentrates mostly on the impact of renewables and fossil energies (*e.g.* Turconi et al., 2013). Life cycle analysis can help to better assess the footprint of nuclear energy.

2.1. Environmental footprint of the French twice-through cycle

Thanks to a bespoke simulation tool entitled NELCAS, CEA has assessed the overall environmental footprint of the current French nuclear fuel cycle (Twice Through Cycle - TTC) considering data obtained over all the nuclear fuel cycle facilities and their whole lifetime (Poinssot et al., 2014). Interestingly, this approach is based on actual data as described in the yearly environmental and safety report produced by any nuclear facility in France thanks to the Nuclear Safety and Transparency Law of 2006. It is 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 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,

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