# RELATIONSHIP BETWEEN SMR AND PLANETARY BOUNDARIES

A mitigation strategy for the global environmental crisis

PRIETO V. CAMILO - AUTHOR

Javeriana University

Bogotá, Colombia

camilo-prieto@javeriana.edu.co

PATIÑO G. DIEGO – OTHER AUTHOR

Javeriana University

Bogotá, Colombia

patino-d@javeriana.edu.co

**Abstract**

Scientific evidence indicates that of the 9 planetary boundaries that have been defined, 6 have been exceeded. High CO2 emissions, land use change, disturbance of nitrogen and phosphorus cycles, damage to the integrity of the biosphere, the effects on fresh water and the excessive emergence of new entities are the geophysical bases of the global environmental crisis. In this article, we analyze the future potential of SMRs modular reactors in mitigating the global environmental crisis and its beneficial relationship with planetary boundaries. This paper calculate the total land-use intensity of energy (LUIE) and we find that SMRs can require between 6.092 ha/TWh/y to 9.98 ha/TWh/y. Additionally, the life cycle (LCA) of the SMR is reviewed, comparing its variables with other types of generation sources. Annually, fossil fuel emissions are responsible for the deaths of 5,1 million people in the world. The nuclear energy industry is the only one in its field that is responsible for waste management and the emissions associated with its activity have a low impact on air quality. The implementation of SMRs in various non-interconnected populations in LATAM, where energy based on coal or liquid fuels is still generated, can be a very relevant. Additionally, the desalination with SMR can improve access to drinking water in communities vulnerable to climate change. In conclusion, SMRs are technologies that contribute to facing the global environmental crisis beyond reducing CO2 emissions. They achieve more efficient use of the land, demand less natural resources than other generation sources and are a tool to improve air quality and the availability of drinking water.

## INTRODUCTIOn

In the study of the global environmental crisis, science has established nine fundamental processes since 2009 that define the safe conditions within which humanity can operate without causing irreversible and harmful changes to the Earth system. These processes are known as planetary boundaries and are defined as follows: climate change, biodiversity loss, disruption of nitrogen and phosphorus cycles, ocean acidification, freshwater use, land-use changes, atmospheric aerosol loading, introduction of new chemical entities, and integrity of the ozone layer [1]. Analogously, they can be understood as the planet's vital signs. The relevance of these boundaries lies in their ability to provide a scientific framework that guides human actions towards sustainability, by warning about the potentially catastrophic consequences of transgressing these thresholds. Respecting these boundaries is crucial for maintaining the stability and resilience of the Earth system, thus ensuring the well-being of future generations.

Focusing solely on climate change, although critical, can be problematic because it ignores other equally fundamental dimensions of global sustainability. In fact, as of 2024, the only ones that have not been transgressed are: ocean acidification, atmospheric aerosol loading, and ozone layer integrity. Human actions have led to the other six being in risk values [2].

Various energy sources, especially fossil fuels, have a significant impact on several of the planetary boundaries, exacerbating environmental problems and destabilizing the Earth system. The burning of coal, oil, and natural gas is the main source of CO2eq emissions, contributing to the disruption of the planet's energy balance. Besides climate change, the extraction and burning of fossil fuels, mining, and industrial processes disturb other planetary boundaries. For example, the processing of these resources releases a large amount of pollutants and particles into the atmosphere, affecting the atmospheric aerosol load and degrading air quality. It is estimated that approximately 5.13 million annual deaths are attributable to emissions produced by the burning of fossil fuels [3]. This not only has direct consequences for human health but also impacts terrestrial and aquatic ecosystems. Indeed, the increase in CO2 emissions affects ocean acidification, as the CO2 absorbed by the oceans turns into carbonic acid, altering marine chemistry and adversely affecting calcareous organisms such as corals and mollusks, essential for marine biodiversity [4].

Likewise, all energy sources can have relevant effects on the use of water and land. Collectively, the use of fossil fuels represents a critical challenge to maintaining within safe limits the stability of the systems that sustain life on Earth, highlighting the urgent need to transition to more sustainable and less invasive energy sources. Life Cycle Assessment (LCA) allows for the comparison of various environmental parameters, other than CO2eq emissions. This methodology is used to evaluate the environmental impacts associated with all stages of a product's life, from the extraction of raw materials to its manufacturing, use, and final disposition. In the context of energy sources, LCA is fundamental for understanding the environmental implications. Some aspects that can be quantified in this type of analysis include: CO2eq emissions and land-use intensity (LIU). It is also possible to establish the number of deaths per TWh per year, related to pollution and accidents. When reviewing aspects relative to nuclear reactors (LR), it is found that, compared to other energy sources, they have the lowest values of: GHG emissions (5.13 gCO2eq/kWh) [5] and an average of total land-use intensity 15 ha/TWh/y [6]. Furthermore, it is relevant to highlight that, in terms of deaths associated with pollution and accidents, nuclear energy presents the safest values of all sources with a value of 0,03 deaths per TWh per year (deaths/TWh/y) [7], in contrast to fossil fuels which range from 2.8 deaths/TWh/y to 24,6 deaths/TWh/y for coal. Using the estimate made in 2023, which mentions that 5.13 million deaths related to fossil fuels occur annually, this value rises to 37,3 deaths/TWh/y. To date, no deaths related to any project under construction or in operation of the SMRs registered in the ARIS database of the IAEA have been reported.

Considering that one of the planetary boundaries is the use of freshwater, it is important to highlight that through the use of cogeneration, SMRs can play a very relevant role in increasing the availability of fresh water thanks to the application of different desalination technologies, whether through the use of thermal energy, as in the case of evaporation, or with the use of electrical energy if reverse osmosis is considered.

This study proposes the calculation of the emission factor (EF), total land-use intensity (LIU) indicators, and a brief review of the advances in desalination projects related to SMRs.

2. METHODOLOGY

We based our research on peer-reviewed scientific literature using the SCOPUS, Sciencedirect, and ARIS databases from the IAEA. Using this data, we conducted an analysis for three specific aspects of SMRs: land use intensity, emission factor according to LCA, and the potential contributions of SMRs to the availability of fresh water in relation to desalination technologies. In the case of land use intensity, no specific values for SMRs were found, only for large reactors (LR), so a mathematical model was selected that allowed calculating the land use intensity taking into account the LCA and the data on operational area use described in the design datasheets included in the ARIS database from the IAEA.

**2.1 Calculation of Total Land Use Intensity**

The formula to evaluate direct land-use intensity of energy (F. 1) requires dividing the area occupied by the SMR installation by the amount of energy generated over a year. It is important to note that the area dedicated to uranium mining, conversion, and enrichment, we call indirect land-use of energy (F. 2) [8-9]. Using this variable makes a difference between the exclusive use of the operation, which if analyzed in isolation, can create a bias in the interpretation of the data. Indeed, the total land-use intensity of energy is the sum of direct and indirect LUIE (F. 3).

$LUIE$direct$= \frac{A\_{direct}}{Energy} \left[\frac{ha\*y}{TWh}\right]$

Formula 1: Direct land-use intensity of energy

$LUIE$indirect$= \frac{A\_{indirect}}{Energy} \left[\frac{ha\*y}{TWh}\right]$

Formula 2: Indirect land-use intensity of energy

$LUIE$total$= \frac{A\_{indirect}+A\_{direct}}{Energy} \left[\frac{ha\*y}{TWh}\right]$

Formula 3: Total land-use intensity of energy

We collected original data registered in the ARIS database of the IAEA for each of the SMR designs recorded up to December 2023. From there, we took the data on the area that each of the SMR models would occupy and their electrical power. To establish the plant factor, we assumed a maximum of 95% and a minimum of 80.2%. These values correspond to those reported by NuScale and the corresponding value of the average plant factor in 2022 for LRs worldwide.

To estimate the indirect area related to the extraction and processing of uranium, a value of 0.08 ha/TWh/y was taken, and for the indirect area associated with waste disposal, a value of 0.012 to 2.9 ha/TWh/y. This value is not taken into account for those SMR designs that use MOX because this fuel is obtained by reprocessing. In the case of LRs, several authors add the value related to the exclusion zones around the two main nuclear energy accidents at Chernobyl in Ukraine (260,000 ha) [10] and Fukushima in Japan (63,000 ha) [6]. For the case of SMRs, this was not included because it is a different nuclear technology. If included, they would add to the calculation 3.9 ha/TWh/y.

**2.2 Calculation of GHG Emission Factor**

To determine the emission factor, values were taken from the LCA calculations obtained from the design of NuScale and Westinghouse AP300, measured in CO2eq/kWh. These emissions are related to the fuel cycle and the activities associated with the operation of the reactor. Additionally, emissions related to fuel production were compared.

**3. RESULTS**

Below are the results found to assess whether there is a favorable relationship between SMRs and the planetary boundaries of climate change and land use.

**3.1 Land Intensity Use**

After reviewing the data on the direct occupied area of the designs included in the ARIS database of the IAEA, it was found that the average direct LIU is 6 – 7 ha/TWh/y. See Table 1. It can be identified that SMRs of “Molten Salt” and “Fast Neutron Spectrum” have the lowest land requirements for generating 1 TWh/y. Using the lower limit of the waste area and direct LIU, the result obtained is 6.092 ha/TWh/y; using the upper limits of the indirect waste area and the direct area, the value reaches 9.98 ha/TWh/y, hence an mean for this range of 8.036 ha/TWh/y. By reviewing the total LUIE values ​​of other energy sources [6], it can be verified that SMRs make highly efficient use of the land. See Table 2.

TABLE 1 DIRECT LUIE ACCORDING SMR TYPE

|  |  |  |
| --- | --- | --- |
| SMR Type  | ha/TWh/yCF 95% | ha/TWh/y CF80.2% |
|  Land based Water Cooled Reactor SMR | 5 | 5 |
|  Marine based Water Cooled Reactor  SMR | 8 | 10 |
| Fast Neutron Spectrum SMR | 4 | 4 |
| Hight Temperature Gas Cooled SMR | 10 | 10 |
| Molten Salt SMR | 2 | 3 |
| Microreactores  | 7 | 9 |
| Mean Direct LUIE | 6 | 7 |

TABLE 2 TOTAL LUIE MEAN BY ENERGY SOURCE

|  |  |
| --- | --- |
| Source of energy | LUIE total (ha/TWh/y) Mean |
| Hydroelectric  | 15000 |
| Ground-mounted PV | 2100 |
| Natural gas  | 410 |
| Wind | 170 |
| Nuclear LR | 15 |
| SMR  | 8 |

**3.2 GHG Emission Factor**

The analysis led by Godsey [11] carried out a life cycle assessment for the NuScale SMR design and calculated that the emission factor corresponds to 4.6 g CO2eq/kWh. Carless, Griffin [12] studying the Westinghouse SMR-PWR, calculated a range of 5.9 to 13.2 gCO2eq/kWh. See Table 3. In the composition of the emission factor, it can be concluded that 7% corresponds to construction, 17% to uranium mining, and more than 70% is related to conversion and enrichment of the fuel. If enrichment is carried out using centrifugation, the related emissions can be 0.4 gCO2eq/kWh, but if performed by diffusion, the value rises to 27.7 gCO2eq/kWh. This is because the gaseous diffusion method consumes about 9000 MJ/SWU, while modern gas centrifuge plants require only about 180 MJ/SWU [13].

TABLE 3 EMISSION FACTOR BY SOURCE

|  |  |
| --- | --- |
| Source of energy | Emission factor (gCO2eq/kWh) |
| SMR NuScale | 4,6 |
| SMR Westinghouse iPWR | 5,9 - 13,2 |
| Large reactors | 5,13 |

**3.3 Fresh Water Availability**

Among the cogeneration possibilities of this type of reactor are urban heating and desalination [13]. This is a technology in which the nuclear industry has experience, as is the case in Japan, where in ten sites that have limited access to fresh water, nuclear power plants are equipped with cogeneration and water desalination plants. Desalination associated with SMRs can be carried out by technologies using heat, such as in the case of condensation, and also by reverse osmosis which requires electrical energy [14]. South Korea has developed a design of a small nuclear reactor for cogeneration of electricity and potable water. The 330 MWt SMART reactor (an integral PWR) has a long life span and only needs refueling every three years. The main concept has the SMART reactor coupled to four multi-effect desalination (MED) units, each with a thermal vapor compressor and producing a total of 40,000 m3/d, using 90 MWe [15]. Parametric studies have been conducted on designs of a NuScale SMR of 160 MWt, to simultaneously supply electricity and heat for desalination. This eight-module prototype could produce 190,000 m3/d and contribute to the power grid between 227 MW and 348 MW [16].

4. CONCLUSIONS

The review of the literature and the data obtained allow us to conclude that SMRs can be a very relevant contribution to the global environmental crisis. The fact that they have a low land use intensity makes them highly efficient in this respect. Additionally, they are a source of low-emission generation and after reviewing the obtained values, we can affirm that their performance in this regard is very similar to that of power reactors. The cogeneration associated with SMRs enables efficient desalination of water, and the implementation of such projects will favor the availability of fresh water.

Thus, with the use of SMRs, variables related to the planetary boundaries of land use, climate change, and availability of fresh water will be positively impacted.

5. DISCUSSION AND FUTURE RESEARCH

It is necessary to develop more research studies that evaluate the LCA of different SMR designs. In the present work, only two designs were reviewed, which are PWRs, and it is necessary to verify if other technologies have different environmental impacts. For example, those designs planned to use MOX, theoretically will have a lower LIUE because this technology, by reprocessing fuel, does not require intensive mining and therefore can also have a lower emission factor than presented in this paper. Over the last 50 years, nuclear energy has saved the world the emission of 70 GT of CO2eq and it is clear that the implementation of SMRs will contribute to increasing this saving.

6. CONFLICTS OF INTEREST

No author associated with this article has disclosed any potential or relevant conflict that could be perceived as an imminent conflict with this research work.

ACKNOWLEDGEMENTS

We appreciate the support provided for this publication by the academic team at the World Institute for Nuclear Security (WINS).

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