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Advances in Modular Reactors: Design, Operation and Future Prospects

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Abstract:

This article thoroughly investigates and analyzes the evolution, design, operation, and future potential of modular reactors in the field of nuclear energy. It addresses the key advantages of these systems, their inherent safety features, as well as the challenges and opportunities they present. Furthermore, the relevance of modular reactors in the context of transitioning towards cleaner and more sustainable energy sources is discussed. The indicator related to the land use intensity in small modular reactors is addressed. Through an interdisciplinary approach, this article aims to shed light on the current state of modular reactor technology and provide an informed perspective on their role in the future energy generation. Results show that land use intensity index is between 0.07-0.08 m^2/MWhy. SMRs have advantages such as safety, mass production and easy transportation; which enables their deployment in remote or isolated areas. Also, this technology can play a key role in the transition to cleaner and sustainable energy production, making them accessible for countries with limited budgets. However, SMRs are in a nascent state and more research is required to address aspects such as environmental impact, human risk, generation efficiency and integration with other energy sources.

Keyworks: Modular reactors; nuclear energy; safety; design; operation; sustainability.

1. Introduction

In recent decades, humanity has become aware of the importance of reducing Greenhouse Gas (GHG) emissions in order to combat climate change. In this regard, a number of targets have been set to reduce carbon in the coming decades. Carbon reduction targets are goals set at national, regional or global level to reduce the amount of GHGs released into the atmosphere. These targets are based on scientific evidence and political commitments made under the United Nations Framework Convention on Climate Change (UNFCCC), its Kyoto Protocol and the Paris Agreement.

The Paris Agreement, signed in 2015 by 195 countries, is the main international instrument for tackling climate change. It aims to keep the global average temperature increase below 2 °C above pre-industrial levels, and to continue efforts to limit it to 1.5 °C (United Nations, 2015).

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To achieve this, countries must submit their Nationally Determined Contributions (NDCs), which are voluntary plans to reduce their emissions and adapt to the effects of climate change.

The signatory nations of the Paris Agreement have committed to reducing GHG emissions by at least 30% and to achieve this goal they must decarbonise their economies. Within the Net Zero scenarios proposed by the IEA, they aim to phase out thermal coal. In 2023 the energy access gap persists: 675 million people have no access to electricity and 2.3 billion people rely on fossil fuels for cooking (IEA; IRENA; UNSD; World Bank, 2023). It is clear that many countries need to increase electricity supply to power their economies.

However, during the generation of this electricity supply, carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) are simultaneously produced, which according to a report by the World Meteorological Organization in 2022, not only generate a rise in global temperature, but also affect the ozone layer (World Meteorogical Organization, 2022) p.10. Being the burning of fossil fuels such as oil and coal one of the main sources of these emissions, added to the limitation of being non-renewable natural resources as Ferrari argues, "in little more than 150 years we have burned almost half of the oil that has been formed in millions of years and we have transferred from the earth's crust to the atmosphere enormous amounts of carbon that are contributing to climate change" (Ferrari, L., 2013 p. 3); and the high operating costs of these fuels, which motivates the urgency to switch to cleaner and more sustainable energy sources.

Based on this evidence on climate change, the finiteness of fossil resources and the importance of ensuring a sustainable energy supply for the future. The transition to renewable energy is a fundamental step in this process, with benefits for both the environment and society.

In this context, this increase must be based on low GHG emission sources in order to meet climate targets. In recent decades, technologies such as solar and wind power have increased their penetration in the electricity matrix in different regions of the world in order to reduce the share of fossil fuels. According to the report of the International Renewable Energy Agency, renewable energy is a key source for reducing greenhouse gas emissions, providing an inexhaustible energy supply, providing an inclusive and climate-sustainable global economy; it will also generate new jobs, transitional reductions in fossil fuel use and further lower fossil fuel costs (IRENA, 2022).

One of the technological alternatives to replace coal is nuclear energy through conventional nuclear reactors. Its high plant factor and low emissions make it an alternative that deserves to be studied. However, the disadvantages of conventional nuclear reactors are their high costs and long construction times. In this respect, the first commercial nuclear power plants started operating in the 1950s. Nuclear power currently provides about 10% of the world's electricity from some 440 power reactors (OWD, 2022). It is the world's second largest source of low-carbon energy with 26% of the total in 2020 (see Figure 1). More than 50 countries use nuclear power in some 220 research reactors (IAEA.org, 2023). In addition to research, these reactors are used for the production of medical and industrial isotopes.

Power System Technology
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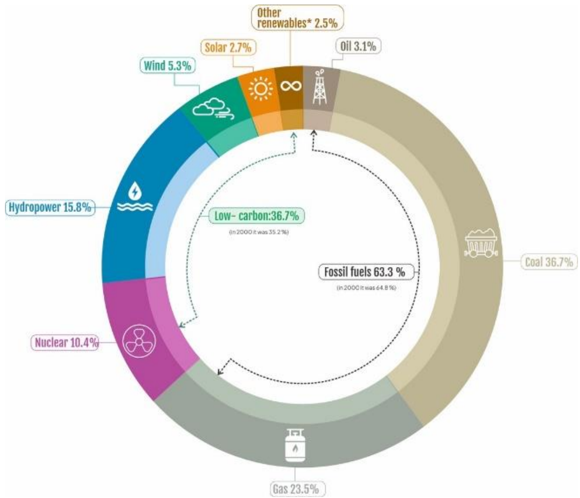

Figure 1: Global electricity production from different sources (OWD, 2022).

Source. Data from (OWD, 2022).

According to calculations taken from Ember's Yearly Electricity Data database; Ember's European Electricity Review and Energy Institute Statistical Review of World Energy recorded in (OWD, 2022), the historical percentage has gone from 17% in 1990 to 10% today. This growth has certainly been affected by the Chernobyl and Fukushima accidents. In 1990, 2000 TWh were generated by nuclear power and in 2022, 2610 TWh will be generated by nuclear power (see figure 2). In other words, only a 30.5% increase in generation in 32 years. This is a far cry from the 252% increase in the share of gas and 128% of coal in the same period of time.

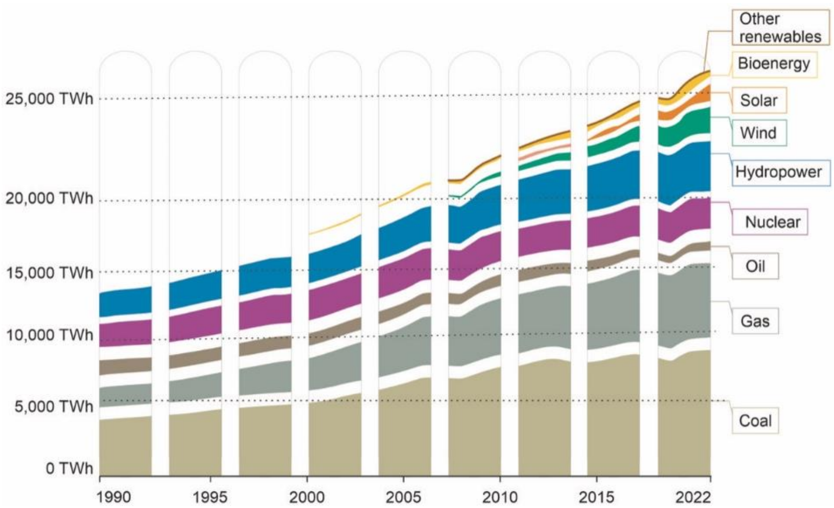

Figure 2: World electricity generated by different sources (OWD, 2022).

Source. From (OWD, 2022).

Power System Technology
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Also, an important factor is the amount of land area required to generate one megawatt per hour of electricity. According to (OWD, 2022) nuclear power requires 0.3 m2/MWh; while other energy sources such as photovoltaic and hydro require 1.2-19m2/MWh, 14-33m2/MWh respectively. This, in addition to its advantages as a low carbon footprint source, also requires less area to supply the required electricity demand.

On the other hand, despite the fact that according to the IAEA (IAEA, 2023) no serious accidents have been recorded in the last decade, the risks inherent to design failures, natural disasters or the product of human intervention that frequently end in regrettable accidents, as in the case of Fukushima in Japan, cannot be overlooked. In these situations, modular reactors present, due to their compact design and integration, decreases in failures and emergency zones (in case of accident/incident) and better protections against the aforementioned disasters (Nuclear Energy Agency, 2021).

As an alternative to the safety, cost and construction time constraints of conventional reactors, there are recent advances in the design and construction of small modular reactors. The modular construction of these devices allows manufacturing within economies of scale. Consequently, modular reactors (SMRs) represent a good option as a replacement for conventional reactors and non-renewable fossil fuels for power generation, since the most important advantages in addition to low greenhouse gas emissions are increased safety against accidents/incidents and ease of construction and operation (Liu & Fan, 2014). However, this technology is still in its infancy and deserves further research. In addition, at the 30th Annual Congress of the Mexican Nuclear Society (Mendoza & López, 2019), it was stated that this type of reactor allows greater flexibility of implementation because they can be part of networks of dispersed populations and with less economic capacity for the construction of conventional reactors.

Furthermore, beyond the use of nuclear energy for consumption in cities, the maritime freight transport industry has been implementing this technology since the 1950s; reaffirming the objective of reducing the carbon footprint, in addition to achieving the benefits of reducing fossil fuel handling costs, reducing dependence on fossil fuel and facilitating the transition to the use of alternative fuels (Hindaris, et al., 2014). The application of modular reactors in marine and underwater vessels is due to the development of new technologies, materials and more effective systems. These allow better construction techniques, operation and control of the reactors.

The evolution of modular reactors is a topic that has been the subject of numerous studies over time. The development of modular reactors has been driven by the need for sustainable and safe energy solutions, leading to significant advances in their design and operation. This continuous development is essential to maintain the relevance of nuclear technology in a context of growing environmental awareness.

Reaffirming what was proposed by (Liu & Fan, 2014), the advantages associated with modular reactors include a smaller environmental footprint, higher nuclear fuel efficiency and lower risk of nuclear accidents (IAEA, 2022). These advantages have significant implications in both economic and environmental terms and play a key role in global energy policy decision-making.

Power System Technology
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On the other hand, according to the IAEA, there are more than 80 SMR designs under development and implementation at different stages in IAEA member states. For example, the floating power unit "Akademic Lomonosov" in the Russian Federation was connected in 2019 with 2 KLT-40S modules, to be commissioned the following year. The HTR-PM in China was connected to the grid in December 2021. CAREM25 in Argentina is under construction and is expected to reach first criticality in 2026. Construction of the ACP100 in China started in July 2021 and is scheduled to start commercial operation by the end of 2026. Similarly, the BREST-OD-300 in the Russian Federation began construction in June 2021 and is expected to be completed in 2026. And finally, the NuScale Power Module™ in the United States gained US NRC standard design acceptance in 2020 (IAEA, 2022).

1.1. Small Modular Reactors and types

The IAEA classifies as SMRs reactors with a power generation capacity of less than 300MW, and whose modules and systems are easy to manufacture and transport on demand (IAEA, 2022). These reactors have the same operating principles and are just as safe as conventional reactors (Vinoya, Ubando, Culaba, & Chen, 2023). They are also much cheaper than their counterparts in terms of manufacturing/construction. Since Lovering analysed the costs of 58% of the world's nuclear power plants (NPPs), he found that there is a considerable increase for the United States, while other countries including India, Japan and South Korea have a much more moderate increase (Lovering, Yip, & Nordhaus, 2016). There are also different classifications of SMRs, depending on their cooling system (see Figure 3) or type of fuel used (IAEA, 2022).

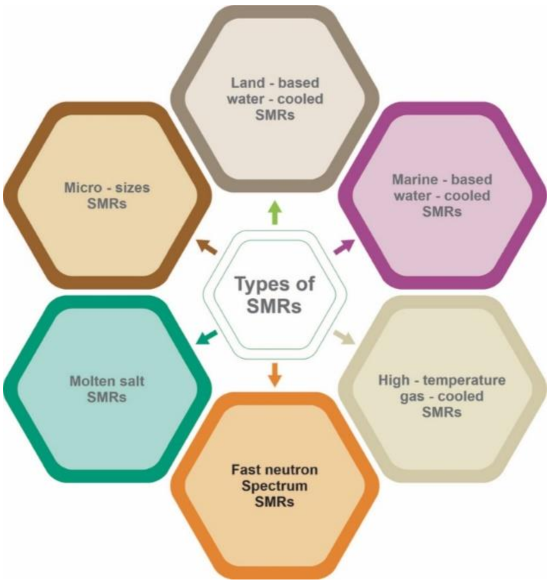

Figure 3: Classification of SMRs by IAEA.

Source. Data from (Vinoya, Ubando, Culaba, & Chen, 2023) and own elaboration.

Power System Technology
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According to Figure 3, terrestrial water-cooled SMRs take advantage of the technology conceived in most large operating power plants, consisting of water-cooled reactors. Second, marine water-cooled SMRs provide many flexible deployment options. Some of them have been deployed on nuclear icebreaker ships. KLT-40S, deployed on the Akademik Lomonosov. Third, high-temperature gas-cooled SMRs known as HTGRs provide high-temperature heat (≥750 °C) that can be used for more efficient electricity generation, a variety of industrial applications, as well as cogeneration. Fourth, liquid metal-cooled fast neutron spectrum SMRs use liquid metal coolants, including sodium, pure lead and lead-bismuth eutectics. The fifth type, molten salt SMRs, is one of the six Generation IV nuclear reactor designs. Molten salt SMRs or MSRs promise many advantages including increased safety due to the inherent property of molten salt, a high temperature system resulting in high efficiency and flexible fuel cycle. Finally, Microreactors have emerged as an unprecedented development trend in very small SMRs designed to generate electrical power typically up to 10 MW. They use different types of coolant, including light water, helium, molten salt and liquid metal. This technology promises future niche markets for electricity and heat, such as powering microgrids and remote off-grid areas, restoring power quickly in communities affected by natural disasters, and providing faster support for the restoration of critical services (e.g. hospitals, water supply) and seawater desalination (IAEA, 2022).

1.2. Modularisation of SMRs

Modularisation of nuclear reactors is understood as the process of converting the design and construction of an NPP into smaller modules that can be easily transported and manufactured for subsequent assembly where required (Gen- IV International Forum/EMWG, 2007). In other words, the complete modularisation of LRs allows the design and construction of advanced small nuclear reactors, which can be mass-produced and transported to a site for installation. A low degree of modularisation, on the other hand, will allow the fabrication and subsequent assembly of its components in the same area (Locatelli & Mignacca, Small Modular Nuclear Reactors, 2020). Also, a feature of modularisation is that by interconnecting several SMRs, the total electrical power generated will be the sum of all the modular reactors (Vinoya, Ubando, Culaba, & Chen, 2023), which allows to meet the increased energy demand at such junctures. Finally, the implementation of two or more SMRs in the same location can generate greater economic benefits, thanks to the fact that assembly and implementation costs, such as the cost of the area, personnel training, among others, are shared with the first module (Vinoya, Ubando, Culaba, & Chen, 2023), (Locatelli & Mignacca, Small Modular Nuclear Reactors, 2020) and (Boarin & Ricotti, 2014).

1.3. Modular reactor design

The designs of modular reactors are currently more standardised and their operation is based on the thermal reaction of enriched uranium using light water as a moderator to reduce the kinetic energy of neutrons, the water used in these reactors can be subjected to pressure regimes (15MPa) or boiling with phase change (Duran, Larriba, & Jimenez, 2022). While the two parts in charge of SMR monitoring and control are the database and the regulation response module, the first part is in charge of extracting the operation/functioning control data and the second

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part sends a response or action based on the feedback information to adjust the SMR operating conditions (Cao, Sun, & Zhang, 2021).

Likewise, data collection either in real time or from a history is of vital importance for safety and critical decision making in modular reactor operation, which is done by PI (Proportional and Integral) controllers that generate an output signal to balance for example the actual temperature with the design temperature of the reactor module (Cao, Sun, & Zhang, 2021). While, in the collection of data taken from external sources, data analysis for operational comparisons with other similar or equivalent stations is also necessary. All this in order to maintain the reliability and safety of the system at all times.

1.4. Modular reactor operation

As explained in the previous section, the type of reactor depends on the condition to which the water is subjected. In the case of pressurised water, the reactor is called PWR (Pressurised Water Reactors), while if the liquid element is subjected to boiling, it is called BWR (Boiling Water Reactors).

The cooling system of PWR SMRs has three cooling sub-systems. The first cooling system has direct contact with the reactor, which is in turn cooled by the second system, which is subsequently cooled by a third system taken from an external source (Duran, Larriba, & Jimenez, 2022). This cooling system is called a passive circuit because it does not require pumps to drive the fluid.

2. Materials and Methods

The materials used in the realisation of this article are mainly scientific articles, reports and up-to-date books dealing with the history, evolution, development, design and safety of modular reactors for civilian use. The aim of this research is to collect up-to-date knowledge, as well as to identify gaps or contradictions in the research subject.

On the other hand, the method employed consists of a thorough review of information describing the current status of modular reactors and their application for civilian use. Since it is essential to identify the context and areas of new developments in the contribution of knowledge. In addition, an adequate literature review promotes the development of new knowledge that starts with research questions arising from one or more problems. In the medium or long term, related ideas and concepts emerge as a result of the synthesis of the literature consulted. Another usefulness of the literature review is the advantage for the researcher to anticipate or estimate the results of previous studies and experiments similar to those that are intended to be scrutinised.

2.1. Conventional reactors (LR)

Conventional nuclear reactors generate controlled fission chain reactions to produce thermal energy in a reaction chamber, which is then used to generate electrical power by boiling water through a Rankine cycle (see Figure 4). The most common types are the pressurised water reactor and the boiling water reactor. Each type has its own specific characteristics and uses.

Power System Technology
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Although conventional nuclear reactors are a reliable and constant source of electrical power, the safe disposal and handling of radioactive waste is a major problem.

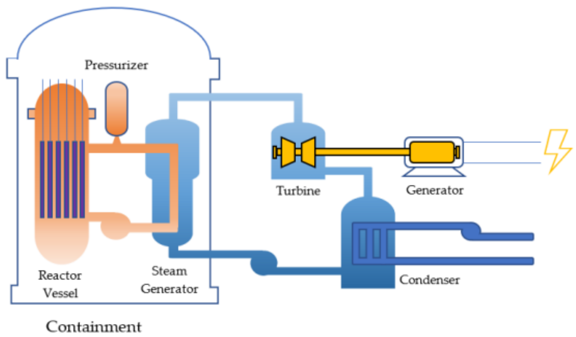

Figure 4: Electric power generation cycle of an LR.

Source. From (Vinoya, Ubando, Culaba, & Chen, 2023).

2.2. Environmental, economic and social sustainability

Environmental, economic and social sustainability or "sustainability of the three baselines" (Sala, 2019) in nuclear technology is an issue that requires a comprehensive and multidimensional analysis, considering the benefits and costs of this energy source in relation to other available alternatives. It also requires adequate regulation and an informed and transparent participation of all actors involved: governments, companies, organisations and citizens.

From an environmental point of view, nuclear energy is a clean source of energy, which does not emit greenhouse gases or other atmospheric pollutants that affect the climate and human health (IAEA, 2023). However, nuclear energy also generates radioactive waste that must be managed safely and responsibly, to avoid risks of accidents, leaks or terrorist attacks. In addition, the extraction and enrichment of uranium, the main nuclear fuel, has a negative environmental impact, consuming natural resources and generating emissions (IAEA, 2023).

From an economic point of view, nuclear power is a competitive source of energy, offering a stable and predictable cost, and contributing to the diversification and security of energy supply (IAEA, 2023). However, nuclear power also involves high costs for investment, operation and maintenance of nuclear power plants, as well as decommissioning and waste management. In addition, nuclear power is subject to fluctuations in the international uranium market and possible sanctions or political restrictions (IAEA, 2023).

From a societal point of view, nuclear power is an energy source that can improve people's quality of life by providing access to clean, affordable and reliable electricity (IAEA, 2023). In addition, nuclear energy can have other societal benefits, such as job creation, technological and scientific development, and international cooperation (IAEA, 2023). However, nuclear energy also raises societal concerns about potential health and environmental risks, as well as the ethical and moral implications of its use (IAEA, 2023).

2.3. Life cycle costs

Power System Technology
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The life cycle of nuclear power plants is the period from design to decommissioning of a nuclear power plant, and must be managed safely and efficiently to ensure the reliability and affordability of electricity. In this case, the capital expended (CAPEX) or overnight cost, so called because it does not take into account the temporary costs inherent in implementation, is the sum of construction costs, ownership costs, contingency and overhead costs (Gen- IV International Forum/EMWG, 2007).

CAPEX= C. construction + C. property + C. contingency + C. general (1)

On the other hand, the capital cost composed of monetary interest during construction and the CAPEX (Buongiorno, Corradini, Parsons, & Petti, 2003).

Cost of capital = CAPEX + Interests (2)

Likewise, the operating costs issued (OPEX) contemplates the fixed and variable costs of operation and maintenance (O&M), fuel costs and plant decommissioning (Lewis, y otros, 2016).

OPEX = Fixed O & M + Variable O&M + Fuel + Dismantling (3)

According to formula 3, it is necessary to take into account the juncture at which the decision to decommission the nuclear plant is made. In the case of catastrophic situations such as Fukushima, the cost of decommissioning escalates to 91 billion dollars (Noguchi, 2021), while for reactors that have reached their useful life this cost can be 0.01-0.16MWh (Boldon & Sabharwall, 2014); or an approximate 15% of the construction cost (IEA/OECD, 2010)..

Finally, the comparison between costs of renewable and non-renewable technologies called Levelised Cost of Electricity (LCOE) is defined as (Vinoya, Ubando, Culaba, & Chen, 2023):

$$LCOE = \frac{\text{VPN of total lifetime costs}}{\text{VPN of energy produced during the lifetime}} \quad (4)$$

$$LCOE = \frac{\sum \frac{\text{CAPEX+OPEX}}{(1+r)^{t}}}{\sum \frac{E_t}{(1+r)^{t}}} \quad (5)$$

Where NPV is the net present value, E_t is the amount of electrical energy produced during a period of time t and r represents the rate of depletion.

3. Current status of SMRs

There are currently 85 SMR design, development, construction and licensing projects, and 4 modular reactors in operation worldwide (IAEA.org, 2023). Table 1 shows the different stages in the development of this technology. According to Table 1, as of today there are 4 SMRs in operation, 3 in the licensing process, 3 under construction and equipping and 75 in early design stages.

Power System Technology
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STATUS	QUANTITY
Preconceptual design	5
Conceptual design	36
Preliminary design	7
In development	1
Basic design	12
Detailed design	12
Final design	1
Certified design	1
Pre-licensing	1
Licensing stage	2
Under construction	2
Operational	3
Operable	1
Equipment production process	1

Table 1: Status of SMR development worldwide.

Source. Data from (IAEA, 2022) and own elaboration.

Thanks to the modularity of this technology, the application of SMRs has expanded worldwide through mass production and ease of transport to the assembly area (Schaffrath, Wielenberg, Kilger, & Seubert, 2021). SMRs can play a decisive role in nuclear energy production, due to their smaller size and power than conventional reactors, inherently safe and based on passive safety systems. In addition, according to Schaffrath, an important part of the new designs is the improvement of safety by avoiding the implementation of costly and extensive assembly or construction lines.

The most important components of SMRs consist of the core, pressuriser, steam generators and cooling pumps (Schaffrath, Wielenberg, Kilger, & Seubert, 2021). According to Vinoya et al. (2023) core refuelling can be performed in the range of 2 to 10 years, and after this time the modular reactor should momentarily cease operation.

One proposal for the reactor core is to moderate this with graphite, zirconium hydride and organic fluid, the latter being used as coolant. This organic coolant allows operation at atmospheric pressure and the use of carbon steel for the reactor tank and primary coolant piping system. Overall, the design provides a power density of 40 kW/L, while reducing the reactor shell size by 40% compared to a pressurised water reactor and significantly reducing plant costs (Shirvan & Forrest, 2016).

Furthermore, a review of advances in ocean nuclear power plants highlights improvements in tsunami and earthquake safety, and the efficient cooling system inherent in these types of reactors (Lee, Kim, Lee, & Lee, 2015). Likewise, (Santinello, et al., 2017) investigates the fluid dynamics and natural convection heat transfer characteristics of seawater, induced by the heating of the Flexblue reactor container submerged at 100 m and with a capacity of 160 MWe,

Power System Technology
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to evaluate the capabilities of the system to reject waste energy to the outside in case of an accident. During the research, a two-dimensional unsteady state CFD analysis was performed to simulate the natural convection flow in the ocean, obtaining predictions for the heat flow distribution, the surface temperature profile of the hull and the heat transfer coefficient. The results showed that the heat transfer process is globally satisfactory to ensure the safe cooling of the reactor. But another 3-D CFD simulation is needed.

In the field of Microreactors, they are generally defined as SMRs with a power output in the range of 1-20 MWe. They can operate as part of the grid, independently of the grid or as part of a microgrid to produce electricity and process heat. According to (Testoni, Bersano, & Segantin, 2021), the main advantages are small size, simple plant layout and fast installation on site. And the main challenges are limited fuel availability, safety/proliferation risk and licensing process. Finally, Testoni et al. perform an economic analysis showing that, due to an economy of scale, despite the reduction of capital cost, micro reactors are not cost-competitive with large nuclear plants, although they perform better against technologies with similar scale and application, such as diesel generators and renewable sources in microgrids.

Another study by (Zheng, Wu, Wang, Chen, & Zhang, 2018) analyses six different types of fourth-generation nuclear reactors and concludes that the thorium-based small modular molten salt reactor is the most promising option to bring nuclear power into the new era of meeting market demand while maintaining maximum safety at an affordable capital cost. The paper also demonstrates the potential to produce radioisotopes and process heat in a thorium-based molten salt reactor. On the other hand, (Tak, et al., 2015) reviewed the feasibility of ultra-long cycle operation in a compact liquid metal cooled compact fast reactor (LMR). The material performance was evaluated in relation to the long cycle operation and the compact sized fast reactor, highlighting thorium for its thermal conductivity and expansive characteristics, and sodium as a good coolant element.

In terms of safety, (Hussein, 2021) indicates that most of the emerging small modular reactor (SMR) designs resemble the older reactors that were designed in the early days of nuclear technology. For Presure Water Reactors (PWRs), he suggests that they can be modernised using fossil fuels to take advantage of their infrastructure. For High Temperature Gas Reactors (HTGRs) and Molten Salt Reactors, experience with the operation of these older reactors can contribute to the licensing of new SMRs, finding that some safety concepts have already been tested and their feasibility demonstrated. And for liquid metal-cooled reactors, careful control of cooling is required.

Also, (Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020) suggests that SMRs take advantage of the physical laws of gravity to achieve good levels of safety and reliability, and that several designs make use of passive safety systems (PSS) to comply with regulations and provide protocols for emergency situations. However, (Hidayatullah, Susyadi, & Subki, 2015) concludes that SMR designs and concepts face the need to be modified or redesigned to achieve licensing, in addition to achieving economic operational competitiveness through innovative concepts to usher in a new era of nuclear energy.

Power System Technology
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(Yin, et al., 2018) conducted a research that focuses on the safety assessment of the reactor core for severe accidents and is part of the overall assessment of SMR safety characteristics for residual risk posed by severe accidents. The results include fuel pellet temperature distribution, fuel cladding, coolant flow rate and hydrogen mass change with time.

Neutron studies applied to microreactors indicate a number of positive reactivity coefficients in an infinite lattice system, but when modelling a finite system with a molten salt as coolant, the coolant temperature reactivity coefficient becomes negative, the vacuum coefficient becomes strongly negative and the moderator temperature coefficient becomes negative to weakly positive. suggest that the proposed design should have acceptable safety performance. The file also discusses the economic and technical challenges associated with microreactors and presents suitable coolant options for natural convection cooling. More detailed analyses and plant studies are suggested to evaluate the behaviour and operating conditions of core and system materials (Peakman, Hodgson, & Merk, 2018).

Furthermore, (Serra, Lozano, Ramos, Ensinas, & Nebra, 2009) highlight process integration and polygeneration as tools to increase natural resource efficiency and minimise environmental impact.

Whereas, (Locatelli G., Fiordaliso, Boarin, & Ricotti, 2017) assess the technical feasibility of coupling a nuclear power plant with hypothetical cogeneration plants that produce diesel-like fuels from pyrolysis of plastics, desalinated water, waste wood pellets or hydrogen from water splitting. The paper also discusses traditional methods of load following in nuclear power plants and how cogeneration can be a more efficient alternative.

(Ingersoll, Houghton, Bromm, & Desportes, 2014) describes NuScale's small modular reactor design that is particularly suitable for cogeneration of electricity and clean water. The plant design provides a cost-effective solution for expanding global desalination capacity, thanks to its enhanced safety, improved affordability and deployment flexibility. Similarly, (Locatelli G., Fiordaliso, Boarin, & Ricotti, 2017) mention cogeneration as an option to facilitate load following more effectively in small modular reactors.
Additionally, (Frick, Doster, & Bragg-Sitton, 2018) describe the design and operation of a responsive thermal energy storage (TES) system for small modular reactors (SMRs) used to absorb grid variability caused by daily changes in load demand and renewable intermittency. And it concludes that coupling a sensible heat TES system to an SMR allows the reactor to operate at full rated output during periods of varying electrical demand by shunting steam to the TES system during periods of excess capacity.
An innovative study by (Wang & Yin, 2020) discusses the design and exergy evaluation of a novel parabolic trough solar-nuclear combined system. The proposed system combines a parabolic trough solar thermal system and a small modular reactor based on pressurised water reactor technology for electricity production and seawater desalination. The paper presents a detailed description of the system, the results of operational and exergy performance evaluations, and concludes that solar energy has a significant impact on increasing the electricity production and energy efficiency of the combined solar-nuclear system.

Power System Technology
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Focusing on seawater desalination, (Ghazaie, Sadeghi, Sokolova, Fedorovich, & Shirani, 2020) conducted a study that focuses on the thermoeconomic analysis of combining small modular reactors (SMRs) with hybrid desalination (HD) plants. The desalination thermodynamic optimisation programme (DE-TOP) of the International Atomic Energy Agency (IAEA) was used to perform an integrated SMR-DP thermodynamic analysis. Several SMR coupling schemes to HD plants were suggested. It was found that the use of relatively hot water from the SMR condenser leads to a reduction of the total desalination cost from 6.5% to 7.5%, where the electricity produced and the hot steam extracted from the low-pressure turbine were used to drive the HD system.

3.1. Economic study of SMRs

From a general perspective, SMRs have great potential in the energy and industrial sector due to their small size and simple integration plan. Thanks to their modularity, these reactors can be built off-site, considerably reducing the difficulty of integration and the activation time, reducing manufacturing costs and mitigating the associated risks. However, there are conflicting views on their economic viability, which will be addressed in this section through the relationship between LCOE and the technology under development.

First, (Agar, Goodfellow, Goh, & Newnes, 2018) employ a novel Analytical Hierarchical Process (AHP) with pairwise comparisons obtained from nuclear cost experts to rank different factors in terms of their relative importance in the near-term commercial success of a deployable SMR. Each expert provides a different set of rankings, although project financing cost is consistently the most important for successful commercial deployment of the SMR.

Similarly, (Lokhov, Cameron, & Sozoniuk, 2013) focuses on the economic and market analysis of small reactors. It concludes that nuclear reactors, whether with a large reactor or small modular reactors (SMRs), are competitive with many other electricity generation technologies in a significant number of cases. However, SMRs have particular characteristics and requirements that set conditions for their implementation.

On the other hand, (Aydogan, Black, Taylor Black, & Solan, 2015) quantitatively and qualitatively compare most LW and ADV-SMR reactors with respect to reactors, nuclear fuel, confinement, reactor coolant systems, refuelling and emergency coolant systems. They conclude that SMRs have the potential advantage of reducing the perceived costs of conventional reactors through savings due to modularisation, mass production, design simplification and passive safety systems.

In addition, (Black, Aydogan, & Koerner, 2019) focus on the economic viability of modular small modular light-water nuclear reactors (SMRs). They present a general methodology for assessing economic viability using levelised cost of electricity (LCOE). The study concludes that due to low direct and indirect capital costs it would generate low LCOE rates, compared to LRs.

(Maronati, Petrovic, & Ferroni, Assessing I2S-LWR Economic Competitiveness Using Systematic Differential Capital Cost Evaluation Methodology, 2018) present a systematic differential economic evaluation approach to assess the costs of nuclear power plants. In particular, to evaluate the costs of the Integrally Safe Light Water Reactor (I2S-LWR). In conclusion, the study revealed that the I2S-LWR design allows cost reductions between 5.84% - 13.02%.

Power System Technology
ISSN:1000-3673

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While (Lloyd, Roulstone, & Lyons, 2021), found that a degree of modularisation of 0.8 reduced from $9855/kWe to $5470/kWe or equivalent to 45% capital cost savings. Meanwhile, (Boldon L., Sabharwall, Bragg-Sitton, Abreu, & Liu, 2015), suggest that for SMRs with power generation below 35MWe, the maximum reduction achieved is 40% in capital costs. On the other hand, (Maronati, Petrovic, Van Wyk, Kelley, & White, 2018) found that thanks to the modularisation of conventional nuclear plants, a reduction in total capital investment costs of up to 42% was achieved.
According the theorical cost estimation approach developed by Roulstone and the manufactured advertised cost, in the figure 5 can be seen that first one approach estimation is higher than the second one. In this case, for BWR and PWR types the cost is around 178-991 USD/MWh for Roulstone approach; while for manufacturer cost, estimations are between 63-316 USD/MWh. The same way, the HTR types are around 99-158 USD/MWh for the first case; while for the second one is 45-89 USD/MWh. Respect the SFR types, Roulstone approach estimates 805-7519 USD/MWh, and manufacturers advertises around 109-386 USD/MWh (Steigerwald, Weibezahn, Slowik, & Von Hirschhausen, 2023).

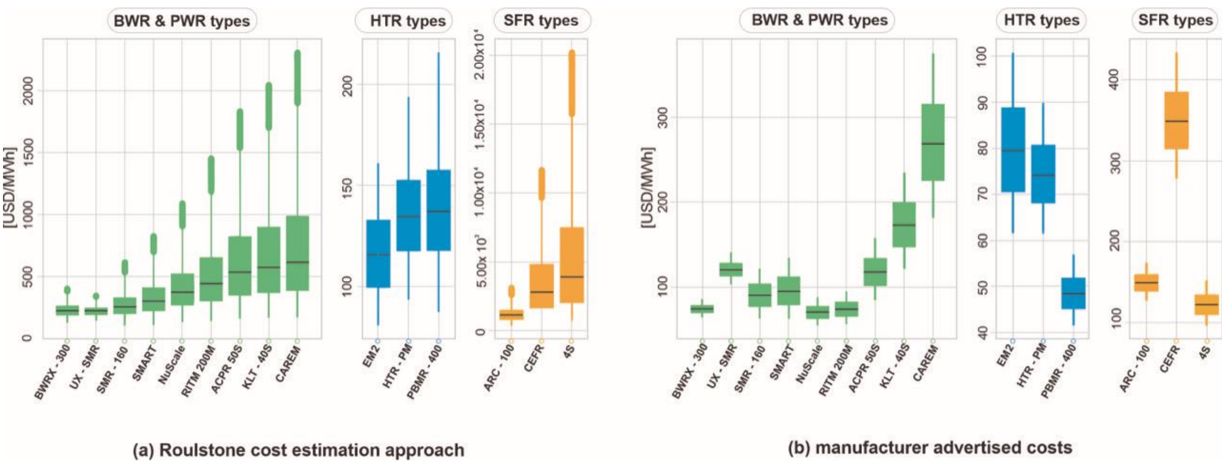

Figure 5: LCOE comparison for (a) Roulstone approach and (b) manufacturers advertised cost.
Source. Data from (Steigerwald, Weibezahn, Slowik, & Von Hirschhausen, 2023) and own elaboration.

Since a global comparison between SMR, LR and other ecological friendly sources, In figure 6 we can see that SMRs still have a high cost of electricity generation, being between 99-7519 USD/MWh respect the other sources. Note that the most economic sources are wind and photovoltaic, due the eolic and solar energy availability. In this sense, SMR and even LR are not economically better than wind and solar photovoltaic sources, but it is necessary be aware that principal difficulties about these both last sources is the variability in the generation capacity.

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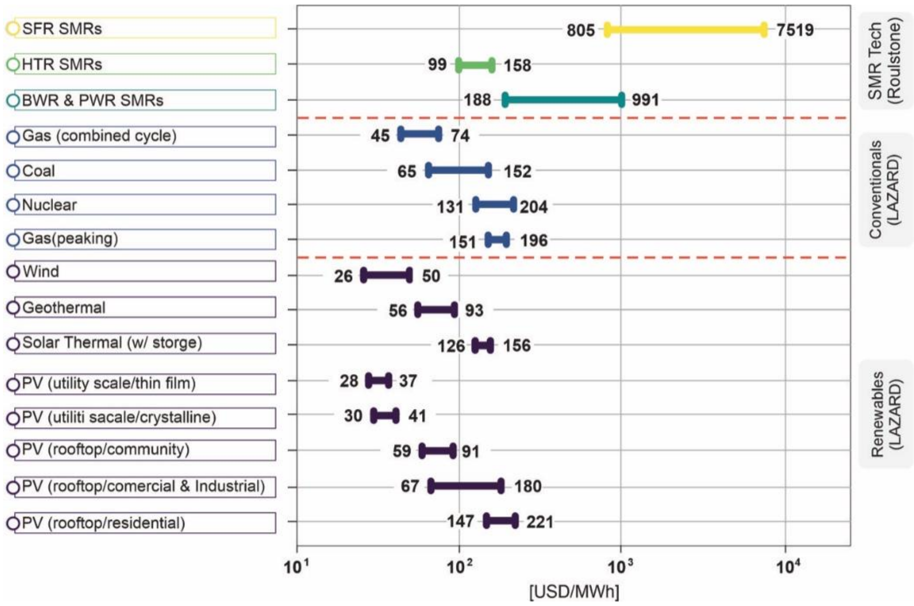

Figure 6: Cost electricity generation for different sources.
Source. Data from (Steigerwald, Weibezahn, Slowik, & Von Hirschhausen, 2023) and own elaboration.

3.2. Socio-political study

One of the main aspects of nuclear energy in the socio-political sphere is society's perception of the technology. With the experience of Hiroshima and Nagasaki, the Chernobyl disaster and Fukushima, society has adopted an attitude that they do not want nuclear facilities near their homes or communities. This attitude is known as "not-in-my-backyard" (NIMBY) and may be an obstacle to the widespread deployment of SMRs (Chew & Choi, 2009). This is because society is aware of the risks implicit in this technology, so according to (Tanaka, 2004), governments should consider the psychological factor of society in the implementation of SMRs.

While (Upadhyay & Jain, 2016) consider that in addition to the advantages of LR modularisation associated with the economic and environmental setting, an improvement in the safety of SMRs is also achieved, which in the long term can change the NIMBY attitude of society. Consequently, governments need to build on these advantages (especially the safety-related one) to moderate society's negative perception of these projects (Zhou, Hu, Tang, Xie, & Zhu, 2023).

Furthermore, the implicit safety improvement of SMRs does not imply that they are free of accidents and incidents, so it is necessary that the personnel operating these plants are aware of the safety culture and that this is measured by their performance (Morrow, Koves, & Barnes, 2014), i.e., that they have active safety policies. In addition, it is necessary for countries considering using this type of energy source to have an independent national authority in charge of regulating these activities, while international entities reinforce existing regulations (Budnitz, Rogner, & Shihab-eldin, 2018).

However, (Ramana & Mian, 2014) argue that SMR implementation is not a universal solution for nuclear power generation, as social and technical factors vary by country and region.

Power System Technology
ISSN:1000-3673

Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

Instead of a one-size-fits-all solution, customised solutions that take into account country-specific social priorities and technical conflicts are needed. Adding to this argument, (Sovacool & Ramana, 2015) claim that engineers and scientists occasionally overestimate the advantages of SMRs to the point of idealising them as a universal solution, forgetting their critical and analytical judgement.

Another important factor is the policies against the proliferation of nuclear fuel, the "nonproliferation regime", to prevent the development of nuclear weapons. In this context, (Prasad, Abdulla, Morgan, & Azevedo, 2015) suggest that SMR designs should consider reductions in maintenance activities that lead to plant shutdown, longer refuelling times and effective communication measures based on wireless systems. Likewise, (Glaser, Hopkins, & Ramana, 2013) argue that SMRs with long-lived cores require fewer resources, but generate high fissile content in fuel consumption, increase the risks of fuel proliferation, and increase the risk of fuel consumption.

3.3. Environmental study

Because fossil fuels generate a large amount of carbon dioxide emissions and other pollutants that contribute to climate change, smog and acid rain. In addition, they are non-renewable resources that are being depleted and whose exploitation implies the destruction of ecosystems and the loss of biodiversity. In the other hand, some friendly ecology energy sources such as photovoltaic power, natural gas, wind power and hydropower still generate high amount of carbon footprint, respect to nuclear power (see figure 7). It has been estimated that SMRs are a good option to replace the use of the other sources mentioned, which is why this study will be detailed in this section.

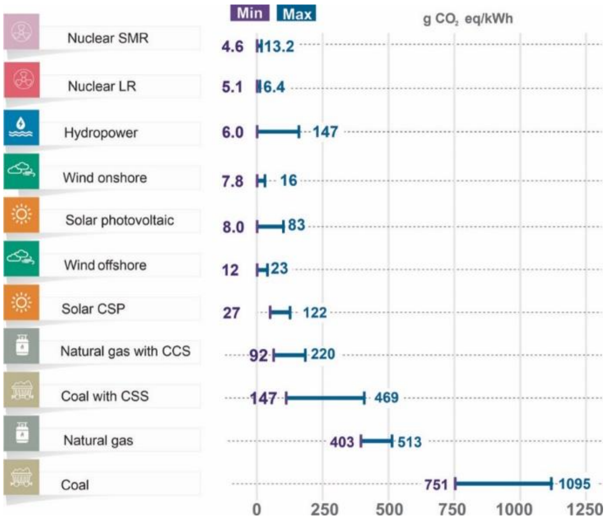

Figure 7: Carbon footprint according to different sources.

In the research conducted by (Boldon L., Sabharwall, Bragg-Sitton, Abreu, & Liu, 2015) it is mentioned that SMRs generate 51 g CO2-eq/kWh, 2.3 g SOx/kWh, and 0.08 g NOx/kWh, while (Koch, 2002) identified from 2 to 59 g CO2-eq/kWh and 0.002 to 0.1 g NOx/kWh for conventional nuclear plants. SMRs are within the permissible range. While (Carless, Griffin, & Fischbeck, 2016) compared emissions from a 300MWe SMRs with 9.1 g CO2-eq/kwh (5.9

Power System Technology
ISSN:1000-3673
Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

to 13.2 g CO2-eq/kwh) and the conventional Westinghouse AP1000 reactor with 8.4 g CO2-eq/kwh (5.5 to 12.1 g CO2-eq/kwh). The latter generating 9% less GHG than the SMR, and limiting the advantages of the SMR only to its modularity compared to the LR.

3.4. Technology and innovation analysis

iPWRs are a type of small modular reactor that use pressurized water as a coolant and moderator. These reactors have innovative and unique features that allow them to have an improved safety margin and greater flexibility for diverse energy applications. One such feature is the integration of key coolant system components within the reactor pressure vessel, which reduces the risk of accidents. Another feature is the use of passive safety systems, which rely on natural physical laws to ensure reactor safety in normal and emergency situations. The text reviews the developmental status of these reactors, of which there are currently about eleven concepts and designs worldwide, and describes their passive characteristics and their advantages over active systems (Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review, 2020).

3.5. Land use intensity analysis

The analysis of land use intensity is useful in terms of the impact that nuclear energy exploitation has on the territory, both in terms of land occupation and land transformation. In this way, this variable allows us to measure the surface area used for the installation and operation of nuclear power plants, as well as the surface area affected by the extraction and transport of nuclear fuels. In addition to assessing the effect that nuclear energy has on other land uses, such as agriculture, livestock, conservation or tourism. And to be able to analyse how land use intensity varies over time and space, and how it relates to other factors such as energy demand, environmental policy or urban development.
Table 2 shows the land use intensity index for the different types of SMRs. It is important to mention that these indices depend on the floor plan factor, which ranges from 80.5% to 92%.

SMR TYPE	$\frac{M^2}{MWhy} MAX$	$\frac{M^2}{MWhy} MIN$
Land-based Water-cooled SMR	0.0539	0.0589
Marine-based Water-cooled SMR	0.0869	0.0993
Fast Neutron Spectrum SMR	0.0420	0.4797
Hight-temperature Gas-cooled SMR	0.1090	0.1255
Molten Salt SMR	0.0280	0.3216
Micro-sized SMR	0.0790	0.0913
Average	0.07	0.08

Table 2: Land Use Intensity Index (IAEA.org, 2023).
Source. Own elaboration.

Power System Technology
ISSN:1000-3673
Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

According to table 2, it can be identified that the SMRs "Molten Salt" and "Water Cooled Land Platform" have the lowest floor area requirements for the generation of 1 MWhy. While in general, the overall average of the indices is in the range of 0.07-0.08. This index, when compared with other sources of electricity extraction, is the lowest, therefore, it can be stated that the use of nuclear energy is the most efficient of all.

4. Future prospects for modular reactors

Because SMRs can offer a clean, secure and flexible source of energy. According to the International Renewable Energy Agency (IRENA), SMRs could play an important role in the energy transition to a low-carbon future, especially in remote or isolated areas, or in combination with intermittent renewable sources. However, SMRs also face a number of technical, economic, regulatory and social challenges that must be overcome for their successful development and deployment. Some of the future prospects for SMRs include

The global SMR market is expected to grow at a compound annual growth rate of 9.2 % between 2020 and 2027, the countries with the highest potential demand for SMRs are expected to be China, Russia, the United States, Canada and the United Kingdom, SMRs could reduce the levelised cost of electricity (LCOE) of nuclear power by 10 % by 2030 and 25 % by 2050, thanks to economies of scale, standardisation, mass production and reduced construction times. In addition, which could contribute to the decarbonisation of sectors that are difficult to electrify, such as shipping, aviation or heavy industry, by producing green hydrogen or synthetic fuels from nuclear energy, it is anticipated that SMRs could improve the safety and management of nuclear waste, by using more advanced designs, passive cooling systems, more robust fuels and closed fuel cycles.

Consequently, SMRs have great potential to be a sustainable energy alternative in the future, but they also require further research, innovation, cooperation and social acceptance for their effective implementation. However, (Vinoya, Ubando, Culaba, & Chen, 2023) suggests that countries interested in this technology should thoroughly analyse the advantages and disadvantages of SMRs through factors such as accessible designs and technology, environmental aspects, political situation and public perception.

Finally, the use of nuclear technology, especially SMRs, is currently part of a transition process towards the use of new, environmentally friendly energy sources. And since their application for civilian use is in its infancy, other ways of using this technology in human activities are currently being developed. One example is the possibility of using them as sources of electricity or energy in space exploration in the future (Duran, Larriba, & Jimenez, 2022). Or the implementation of these in maritime human transport or aerospace. But due to the radiation risk that this technology poses, further research and radiation mitigation or retention strategies are still needed.

5. Results

The reduced dimensions of SMRs compared to conventional reactors make them an attractive proposal for the application of this technology in a wide range of activities ranging from power

Power System Technology
ISSN:1000-3673
Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

generation to the aerospace or pharmaceutical industry, such as heat generation for industry, heating for urban consumption and thermal desalination (Mendoza & López, 2019).

At the same time, the compact dimensions not only translate into less space and greater flexibility of the technology, but also generate a positive impact in other areas such as economics, as it has lower manufacturing costs and is easier to transport, making it accessible to developing countries. This accessibility and universalisation of this technology would be reflected in the economy through the promotion of jobs and higher profits due to the mass production of its components (Duran, Larriba, & Jimenez, 2022). Also, nuclear energy has three important advantages such as zero greenhouse gas emissions, high cost-effectiveness and the reliability of generating energy continuously over long periods of time (Badora, Kud, & Woźniak, 2021).

On the other hand, due to the high criticality and risks involved in operating nuclear technology, international organisations such as the IAEA propose safety principles, requirements and control measures that operating countries must comply with to ensure the safety of people and the environment against ionising radiation (IAEA, 2023). As a result, strategies for correct control and operation measures have been developed and different controllers based on microcontrollers and algorithms have been developed, which analyse the operating conditions in real time and issue corrective actions to avoid potential accidents/incidents.

In addition, radioactive waste management for any nuclear technology operator is also regulated by the IAEA, whose priority is to maintain safe conditions for people and the environment through guidelines on different operations such as reduction, treatment, conditioning and storage (IAEA, 2009).

6. Discussion

After having given an overview of small modular reactors (SMRs) and their application in nuclear energy production, several advantages of SMRs were mentioned. Several advantages of SMRs were mentioned, such as their smaller size and power compared to conventional reactors, their inherent safety based on passive safety systems, and their modularity that facilitates their serial manufacturing and transport to the assembly area (Schaffrath, Wielenberg, Kilger, & Seubert, 2021). These features make SMRs an attractive option for nuclear power generation at various locations.

It also highlights the most important components of SMRs, such as the core, pressuriser, steam generators and cooling pumps. Furthermore, core refuelling can be performed every 2 to 10 years, which allows for extended operation before the reactor must momentarily cease operation (Schaffrath, Wielenberg, Kilger, & Seubert, 2021) and (Vinoya, Ubando, Culaba, & Chen, 2023). In addition, the use of organic refrigerants allows operation at atmospheric pressure and reduces plant costs (Shirvan & Forrest, 2016). An interesting aspect addressed is the use of SMRs in the production of radioisotopes and process heat for application in heating systems.

On the other hand, different studies assessing the economic viability of SMRs compared to other power generation technologies, such as diesel generators and microgrid renewables, show

Power System Technology
ISSN:1000-3673

Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

a broad spectrum of horizons in the solution to global warming. And it is concluded that SMRs of the micro reactor type are not cost-competitive with large nuclear plants. However, they perform better than technologies of similar scale and application (Testoni, Bersano, & Segantin, 2021).

Regarding the analysis of socio-political and environmental aspects related to SMRs. The perception of society towards nuclear energy and the need to consider the psychological factors of society in the implementation of SMRs were mentioned (Tanaka, 2004). Furthermore, the importance of safety and the need for active safety policies in the operation of SMRs, a constant synergy of safety performance evaluation and safety culture among plant workers were discussed (Morrow, Koves, & Barnes, 2014).

Regarding the environmental aspect, it is highlighted that SMRs generate low emissions of carbon dioxide and other pollutants compared to conventional energy sources. In general, a broad view of SMRs was found that addresses several aspects related to their design, safety, economic viability, social acceptability and environmental impact. Although some challenges and considerations are mentioned, the potential of SMRs for safe, efficient and sustainable nuclear power generation is highlighted.

The main discussion on the environmental aspect is based on the worldwide concern about the increase in global temperature caused by the emission of greenhouse gases, with the transition to the use of more environmentally friendly energy sources such as nuclear energy being an important point of attention. The hope placed in this type of energy is due to the economic profitability of generating (electrical) energy with low greenhouse gas emissions (Yim, 2006). However, "low emission" is mentioned because these gases are generated during the upstream and downstream processing of the nuclear fuel in the plant, with the average amount of pollutant gases being 65 g CO2-e/kWh according to (Lenzen, 2008).

Likewise, in a 2013 report by the Polish National Centre for Nuclear Research, it was recognised that although the implementation of modular reactors cannot completely meet the country's electricity demand, this type of modular plant facilitates the electrification of remote, geographically difficult and isolated areas of the country (MRS Bulleting, 2013). This report affirms what was mentioned by (Mendoza & López, 2019) and (Duran, Larriba, & Jimenez, 2022) when mentioning the flexibility of SMRs in countries with complicated geographies and even more so in underdeveloped countries.

In addition, because the demand for electricity to supply cities and small towns is continuous, the organisations in charge of supplying this requirement have to operate perennially. It is in this sense that SMRs are the most suitable for this application; since, being designed to operate for decades, these systems do not require refuelling (Uranium), which eliminates the probability of unexpected shutdown, or potential errors immanent to this process whether due to human or other factors (Tsoulfanidis, 2016).

Another potentially viable feature for SMRs is the cogeneration of hydrogen from the high-temperature hydrolysis of alkaline water, in response to elevated reactor core temperatures in seasons of high energy demand. However, at times of low energy demand, the adjustment is

Power System Technology
ISSN:1000-3673
Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

made by means of bar control in the pressure chamber, which is not a very efficient procedure and does not result in decreases in operating costs (Locatelli G. B., 2018).

In terms of safety, it is worth mentioning that due to the low complexity of SMRs and the high standards of manufacture, construction and implementation of the systems and their mechanisms, the presence of active fault correction and mitigation systems is almost unnecessary, further simplifying the reactors (Nuclear Energy Agency, 2021). In addition, the possibility of locating the reactor in underground facilities adds more safety in terms of natural disasters or accidents/incidents such as aircraft impacts (Liu & Fan, 2014).

7. Conclusions

Small modular reactors (SMRs) offer several advantages, such as their smaller size and power compared to conventional reactors, their inherent safety based on passive safety systems, and their modularity which facilitates their mass production and transport to the assembly area. There are different types of SMRs, such as water cooled, high temperature gas cooled, liquid metal cooled and molten salt cooled, each with their own specific characteristics and applications. In addition, microreactors are less competitive than LRs. Modular reactors can also play an important role in the transition towards cleaner and more sustainable energy sources, contributing to the reduction of greenhouse gas emissions and the provision of clean and reliable electricity.

Significant progress has been made in the design and operation of SMRs, but more research and development is still required for large-scale deployment. Since there are situations where this technology is often idealised as the universal solution to energy needs (Sovacool & Ramana, 2015).

On the other hand, the economic viability of SMRs is an important aspect to consider, with factors such as the cost of construction, operation and decommissioning, as well as competitiveness with other power generation technologies.

Indeed, SMRs offer promising advantages in terms of size, safety and modularity, and have the potential to play an important role in safe, efficient and sustainable nuclear power generation. However, further research and evaluation is required to determine their economic viability and their integration into the existing energy infrastructure.

In this context, according to the sources consulted, a critical appraisal of this emerging technology can be formed based on the low carbon footprint that small modular reactors generate compared to fossil fuels, the latter being costly and non-renewable. Furthermore, according to the land use intensity index, this type of energy has the lowest value ($0.07-0.08m^2/MWhy$), which is indicative of its high energy generation efficiency and the inherent environmental risks and impacts of this technology.

In order to avoid a global temperature increase of 1.5°C, i.e. below pre-industrial levels, established by the Paris agreement on climate change, it was established to replace the current conventional energy generation sources with others that are less harmful to the environment and during this transition process nuclear technology proved to be a candidate that is ideally

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suited to this task because it has a higher generation efficiency than other sources (solar or wind), in addition to its operation can last for several decades continuously.

Additionally, SMRs have much more flexibility to be deployed in remote locations or by countries with limited budgets and developing countries. There is also the possibility of interconnecting them with other modules to provide higher energy demands.

However, despite the encouraging characteristics of this technology, the last decade has seen a reduction in the use of nuclear power, mainly due to the 2011 Fukushima disaster in Japan. In addition, it has also been reported that in some countries this energy does not meet the domestic demand for it, and they have resorted to the use of other sources.

On the other hand, because this technology is still in its infancy, it is necessary to deepen our understanding of the potential damage to human health, the environment and the development of new techniques for retaining ionising radiation in order to extend its application to other areas such as human transport or aerospace.

8. Future Research

It is of vital importance to generate knowledge and understanding of small modular reactors, their operation and processes, in order to subsequently carry out research concerning the control of power generation in the reactor core, to avoid thermal fatigue in the components. Since the adjustment by means of rods in the pressure chamber is inefficient.

Also, taking advantage of new advances in nanotechnology and microcontrollers, it would be of great help to the international scientific community to develop new techniques for temperature control and response to eventual criticality circumstances. Improved reactor and reactor component design techniques and processes would also help to improve reactor reliability and conversely mitigate the likelihood of failure (Liu & Fan, 2014).

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