SMALL MODULAR REACTORS – TECHNOLOGICAL SOLUTION FOR THE GLOBAL ENERGY TRANSITION

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The global energy transition is a crucial step in combating climate change and ensuring a sustainable future. In this context, small modular reactors (SMRs) stand out as a promising solution for producing clean, efficient and safe energy. This paper analyzes SMR technology, its characteristics, its advantages over traditional nuclear reactors and their complementarity with renewable energy sources, highlighting their role in the global energy transition. The novelty of the research lies in proposing a hybrid energy system concept based on small modular reactors integrated with renewable sources and hydrogen production, aimed at optimizing energy production and use and reducing carbon emissions. In conclusion, SMRs represent an important component of the transition to a low-carbon energy system at a global level, but require investments in research, infrastructure, education and regulations to overcome existing barriers and support the development of sustainable energy.

Keywords: small modular reactors, energy sustainability, global energy transition, energy of the future, hybrid energy system, hydrogen

1. Introduction

Climate change and the continued growth of global energy demand are major challenges of the 21st century, requiring a rapid transition to sustainable and low-carbon energy sources [1]. As countries seek to meet new demand and move away from carbon-intensive energy sources such as coal, advanced clean energy sources are vital. Nuclear energy is recognised as a key pillar in this transition due to its ability to provide stable and reliable electricity without greenhouse gas emissions [2]. The 28th Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change (UNFCCC), held in Dubai, reaffirmed

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the importance of nuclear energy in achieving net-zero emissions goals, highlighting the need for innovative technologies such as Small Modular Reactors (SMRs) [3].

SMRs represent a significant innovation in the nuclear sector, with a compact and modular design that facilitates mass production and rapid assembly, thus reducing costs and improving operational safety [4]. These reactors are designed to operate independently or in scalable configurations, facilitating integration into existing power grids and use in remote locations or specific industrial applications [5]. The use of passive safety systems also contributes to reducing the risk of accidents and increasing operational efficiency and reliability [6].

Globally, recent initiatives highlight the importance of investing in advanced nuclear technologies. For example, the International Energy Agency (IEA) highlighted in its Net Zero Roadmap to 2050 the need to triple nuclear capacity by 2050 to meet global climate goals [7]. In addition, at COP28, a coalition of over 20 countries advocated for the integration of nuclear energy into development banks' financing strategies and for strengthening the supply chains necessary for the global adoption of SMRs. Recent bilateral agreements, such as the one between the United States and Ukraine on cooperation in the development of SMRs, reflect the shared commitment to supporting the transition to a sustainable energy system [8].

In light of these developments, this paper aims to review the technological progress of small modular reactors, highlighting their advantages over traditional nuclear reactors, their complementarity with renewable energy sources and their impact on the global energy infrastructure. The study will also assess the potential of SMRs to contribute to achieving global carbon emission reduction goals and support the integration of renewable energy sources into a sustainable energy mix.

The novelty of this research lies in the conceptual proposal of a hybrid energy system that integrates Small Modular Reactors with renewable energy sources and hydrogen production units. This approach provides an innovative pathway for optimizing energy generation and storage, reducing greenhouse gas emissions, and enhancing grid flexibility, thereby contributing to the development of next-generation sustainable energy systems.

2. Small Modular Reactor Technology

Small modular reactors (SMRs) are compact nuclear units with a much smaller capacity than conventional nuclear reactors, but with a significant advantage in terms of modularity and scalability. They are about one-tenth to one-third the size of traditional nuclear power plants, generating about 300 megawatts of electricity (MWe) per unit. The main purpose of SMRs is to improve safety, economic efficiency and flexibility in application, in a context where energy requirements are increasingly diversified and distributed [9].

SMR projects have explored various types of reactors. As illustrated in Fig. 1, the main SMR technologies are classified into four major groups: water-cooled reactors, high-temperature gas-cooled reactors, liquid metal-cooled fast reactors and molten salt reactors. In addition, there are two additional categories – floating nuclear power plants and microreactors – that are derived from the main four. Currently, there is an increasing number of designs; the most recent SMR brochure published by the IAEA presents 83 models [10].

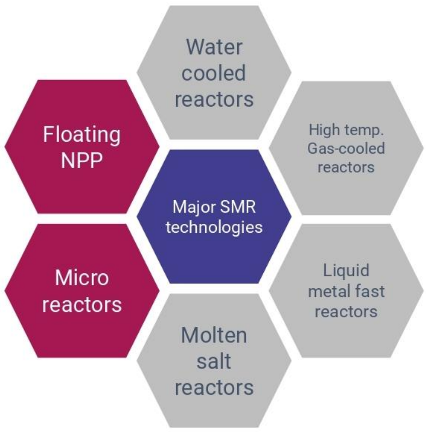

Fig. 1. Key technological categories of SMR technologies [10]

The modularity of SMR reactors gives them a considerable advantage in terms of cost and construction time. They can be manufactured in a manufacturing facility and then transported to the final location, which reduces the risks associated with on-site construction. The ability to add additional modules as energy requirements increase is also another aspect that makes SMRs highly scalable [11].

Another major benefit of SMRs is the integration of passive safety systems, which do not require active cooling equipment, reducing the risks of technical failures and human error. These reactors use natural cooling processes, based on the laws of thermodynamics, thus ensuring the safety of the reactor even under extreme conditions [12].

SMRs are also more efficient than conventional nuclear reactors, optimized to maximize fuel utilization and minimize waste [13]. They provide a constant and reliable source of energy, essential for complementing intermittent renewable energy sources such as solar and wind power.

3. Small Modular Reactors (SMRs) versus traditional nuclear reactors: construction costs, safety and implementation time

This chapter highlights the key aspects that differentiate small modular reactors from traditional nuclear reactors from the perspective of construction costs, operational safety and implementation time, drawing on recent scientific literature.

3.1. Construction Costs and Economic Viability

One of the primary advantages of SMRs is their lower upfront capital costs compared to conventional nuclear reactors. Traditional reactors, such as the EPR (European Pressurized Reactor), require multi-billion-dollar investments and extended construction periods, often exceeding initial budget estimates. For example, the Flamanville-3 EPR project in France witnessed cost overruns from an initial estimate of €3.3 billion to over €12.7 billion [14].

In contrast, SMRs leverage modular construction techniques, enabling factory fabrication and on-site assembly, which significantly reduces construction costs and project risks. According to several studies conducted to date, standardized production of SMRs allows for economies of scale over time, reducing capital costs per installed MW [15] [16].

Despite the cost advantages, the economic feasibility of SMRs remains contingent on mass deployment. Initial SMR projects exhibit higher per-MW costs due to limited production experience and regulatory hurdles. A comprehensive techno-economic suggests that cost parity with large reactors can be achieved when at least 10-15 SMR units are deployed in a coordinated manner [17].

3.2. Safety and Risk Management

SMRs incorporate advanced safety features, including passive cooling systems and inherent design characteristics that minimize human intervention in case of emergencies. Traditional large-scale reactors rely on active cooling mechanisms, which require external power sources, making them more vulnerable to station blackout events.

SMRs benefit from a lower Core Damage Frequency (CDF) and Large Release Frequency (LRF) due to their smaller core size and enhanced containment strategies. It is generally known that the CDF values for SMRs are lower compared to those of large nuclear reactors. [18]

Moreover, the inherent safety of SMRs facilitates their siting in locations unsuitable for traditional reactors, such as remote regions and industrial hubs requiring reliable baseload power [19]. These safety advantages align with international regulatory trends towards risk-informed decision-making and simplified licensing processes.

3.3. Deployment Time and Scalability

Traditional nuclear reactors require extensive construction and licensing periods, spanning many years from the start of the project to connection to the grid. The Vogtle AP1000 reactors in the United States exemplify these delays, with construction timelines stretching beyond 14 years [20].

In contrast, SMRs have the potential to significantly reduce deployment times [21]. Estimates suggest that the construction period for SMRs is approximately 4–5 years for FOAK (first of its kind) and 3–4 years for NOAK (next of its kind) [22]. This reduction in construction time for SMRs is due to their smaller size, simpler design, increased modularization, and the fact that a large part of the components are manufactured in a factory, which allows for mass production and standardization.

A case study on NuScale Power's SMR design demonstrates the feasibility of staged deployment, wherein multiple small reactors can be added progressively to meet grid demand while mitigating financial exposure (World Nuclear Association, 2022). This approach contrasts sharply with the all-or-nothing commitment required for large reactors, which face higher susceptibility to project cancellations and funding withdrawals.

3.4. Examples of SMR projects implemented or in development

Table 1 presents the major technological achievements of SMRs, highlighting the progress made globally. The summarized information comes from various credible sources, including government reports, publications from international organizations, and contributions from key industry players, reflecting a broad spectrum of initiatives and collaborations in the field. SMRs are a versatile solution to the energy challenges of the 21st century, addressing issues such as safety, operational flexibility, and integration into national energy mixes. While designs such as SMART from South Korea focus on compactness and operational efficiency, other initiatives, such as those in the United States (e.g., NuScale VOYGR) and Europe (e.g., Rolls-Royce), highlight the adaptability of these technologies for large-scale commercial uses and integration with renewable energy sources. These projects contribute to reducing operational costs and optimizing the use of existing nuclear resources [23] [24] [25].

Table 1

Significant developments in SMR technologies globally

Country/ Region	SMR Design	Features and Key Projects	Planned Timeline
Canada	GE Hitachi BWRX-300	Natural circulation reactor. First commercial SMR construction in North America	Construction begins in 2025, grid connection in 2028 [26]

France	EDF-NUWARD SMR	PWR design, funded through the France Relance 2030 program. Includes the development of other advanced designs (NAAREA, Newcleo, etc.)	Ongoing development [27]
Japan	HTTR	30 MW thermal reactor used for hydrogen production demonstration	Operational, used for hydrogen projects [28].
South Korea	SMART	100 MW(e) PWR reactor, approved in 2024. Developed in collaboration with Saudi Arabia	Expanded partnerships, including with Canada[23]
	i-SMR	Integrated PWR reactor with a capacity of 170 MW(e), developed by a national consortium	Ongoing development [29]
United Kingdom	Rolls-Royce PWR	470 MW(e) PWR reactor, designed for integration into diversified energy grids	Ongoing development [24]
United States	NuScale VOYGR	Modular reactor with six modules, each generating 77 MW(e)	Licensing and demonstration in progress; potential locations in Europe [25]
	Westinghouse AP300	SMR project under licensing	Ongoing development[30]
	Holtec SMR-300	Modular reactor with a capacity of 300 MW(e)	Ongoing development [31]
	X-energy Xe-100	HTGR reactor, part of Generation IV technologies	Ongoing development[32]
	Oklo Aurora & eVinci	Compact microreactors for various applications	Ongoing development[33]
	MARVEL Project	Research and evaluation of microreactor applications at Idaho National Laboratory	Ongoing research[34]
China	CAP1400 and ACP100	Commercial SMR projects. ACP100 designed for islands and isolated areas; CAP1400 for large-scale use	Pilot projects underway[35]
Russia	RITM-200	Reactor developed for icebreakers and land applications; active commercial implementations	In operation [36]
India	AHWR	Thorium-based project aimed at diversifying nuclear fuel sources	Ongoing development[37]
Argentina	CAREM	First SMR developed in Argentina, with a capacity of 25 MW(e).	Under construction[35]

On the other hand, developments in China and Russia demonstrate the dual-use potential of SMRs: for electricity generation as well as other industrial applications, such as powering desalination plants or providing energy to remote regions. For instance, the RITM-200 reactor, already used for powering icebreakers in Russia, has been adapted for land applications, showcasing technological flexibility [36].

Pilot projects in Japan, such as the use of the High Temperature Engineering Test Reactor (HTTR) for hydrogen production demonstration, underline the role of SMRs in diversifying emerging industrial applications, such as the transition to green hydrogen [28]. Furthermore, Canada has become an important leader in SMR implementation, with projects like the GE Hitachi BWRX-300, which is in the planning stage, demonstrating the potential to sustainably meet energy demands [26].

Expanding the perspective, initiatives in Argentina and India make a significant contribution to promoting nuclear reactors for emerging markets. The CAREM reactor in Argentina and the AHWR in India illustrate these countries' commitment to innovation by implementing SMR technologies for remote areas and utilizing alternative resources such as thorium.

These technological advancements not only offer tangible solutions for the efficient integration of nuclear energy into diverse energy mixes but also contribute to reducing dependence on fossil fuels. Additionally, using SMRs for industrial applications such as desalination and hydrogen production has the potential to accelerate economic development and enhance global energy security. In the long run, implementing these technologies can support the transition to a low-carbon global economy, thus supporting the ambitious climate goals set by the Paris Agreement.

4. SMR versus renewable energy sources: integration, advantages and challenges

SMRs offer unique advantages in integrating with renewable energy sources [38]. Their ability to operate continuously, 24/7, allows them to cover energy demand during periods when renewable production is low. For example, when solar and wind power cannot meet consumption requirements due to adverse weather conditions, SMRs can provide the necessary baseload energy. In addition to providing electricity, SMRs can also be used in other applications, such as the production of hydrogen through thermochemical water splitting. Hydrogen, a clean fuel with multiple uses, plays an important role in decarbonization strategies and can be used in both transport and industry. Furthermore, SMRs are extremely useful in remote regions that are not connected to traditional electricity grids, thus allowing for expansion.

A relevant example supporting the integration of SMRs with renewable sources is provided by the study by Nikolaos et al. [39]. In it, a scenario proposes a hybrid energy system that combines the energy produced by photovoltaic panels, small modular reactors (SMRs) and the grid, with the main objective of generating hydrogen for automotive or stationary applications. According to this scenario, the system architecture includes not only power generation sources, but also an electrolyzer for hydrogen production and dedicated tanks for its storage. The system is designed to cover a varied daily load, thus demonstrating the flexibility and scalability of SMRs when integrated with other renewable energy sources. The complete system architecture is presented in Fig. 2 below.

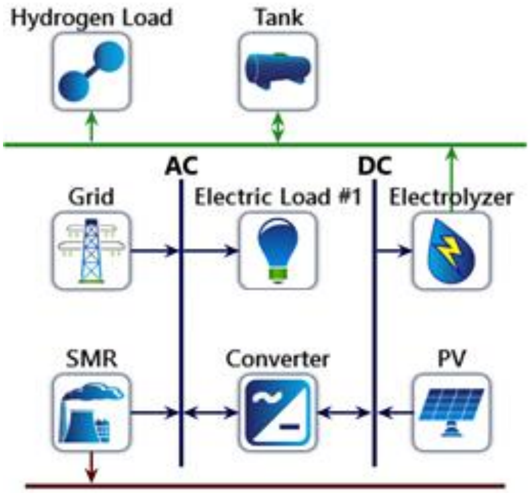

Fig. 2. Architecture of a hybrid system based on SMR, photovoltaic panels and grid [39]

This model clearly illustrates how the use of SMRs can support a versatile energy mix, providing both stable electricity and a clean fuel (hydrogen) for various applications. By simultaneously producing electricity and hydrogen, the system ensures resource optimization and a reduction in greenhouse gas emissions, making it a practical example of the applicability of SMRs in a real-world context.

Building upon this previously published model, the present study proposes its own conceptual adaptation of a hybrid energy system integrating SMRs, renewable energy sources, and hydrogen production units. This conceptual proposal represents the main novelty of the research and focuses on enhancing system flexibility, improving storage capacity through hydrogen conversion, and reducing CO_2 emissions compared to conventional energy mixes. The proposed configuration aims to optimize the interaction between nuclear and renewable technologies, providing a balanced and resilient energy supply suitable for decentralized and future-oriented networks. The main comparative characteristics of conventional and hybrid systems are summarized in Table 2.

Table 2

Comparative characteristics of conventional and proposed hybrid SMR–renewable–hydrogen energy systems

Parameter	Conventional energy system	Proposed hybrid SMR–renewable–hydrogen system
Main energy source	Natural gas / coal power plant	SMR + photovoltaic system
CO_2 emissions	~400 g/kWh	<50 g/kWh
Energy supply profile	Continuous but polluting	Continuous and low-carbon
Integration with renewables	Limited	Full integration with renewables and hydrogen
Energy storage	Absent or minimal	Enabled via hydrogen production and storage
Grid stability	Moderate	High due to hybrid configuration
Application areas	Large centralized plants	Modular, scalable, regional or isolated zones

The comparative analysis in Table 2 highlights that the proposed hybrid SMR–renewable–hydrogen configuration goes beyond traditional energy systems by introducing a multi-purpose operational logic. Instead of focusing solely on electricity production, it enables energy conversion, storage, and reconversion in a single integrated platform. This flexibility allows for better management of fluctuating renewable generation and provides a strategic reserve of clean hydrogen that can be used for industrial processes, heating, or as a feedstock for synthetic fuels. Moreover, by decentralizing energy production into modular hybrid units, the system reduces transmission losses and increases resilience against grid disruptions.

Such an approach transforms the role of SMRs from simple power generators into dynamic elements of a sustainable, interconnected, and low-carbon energy ecosystem. Although the integration of SMRs with renewables brings multiple benefits, there are also significant challenges. One of the main barriers is public acceptance, which can be influenced by concerns about nuclear safety, nuclear waste management and nuclear proliferation. Furthermore, the regulations required for the implementation of SMRs are complex and can vary significantly from one country to another. The initial construction costs of SMR reactors are higher compared to renewable energy sources, and the risks associated with their development and operation can create obstacles to rapid implementation.

However, if these challenges are effectively managed through clear regulations, public education and advanced waste management technology, SMRs can play an important role in diversifying the energy mix and ensuring a constant and reliable source of energy, perfectly complementing renewable energy sources[40]. Implementing SMRs together with renewable sources can help stabilize electricity grids, reduce carbon emissions and support emerging economies that lack renewable energy resources or infrastructure.

5. Long-Term Sustainability of SMRs

The integration of Small Modular Reactors (SMRs) into a diversified and sustainable energy mix represents a significant opportunity for the global energy future.[41] Given that SMRs are small and modular reactors, they are scalable and can be adapted to local needs. Modern nuclear safety technologies allow operations in a much safer framework than conventional nuclear reactors. Another advantage of SMRs is that they can be designed to operate in parallel with renewable energy sources, ensuring a constant energy output and balancing fluctuations in production from renewable sources.

In terms of long-term sustainability, SMRs can be built with a longer lifespan and are less costly in terms of maintenance than traditional nuclear reactors [42]. Additionally, SMRs can use a variety of nuclear fuels and can be designed to minimize the risks associated with the storage of radioactive waste. Therefore, SMRs represent a sustainable option for reducing energy dependence on polluting sources.

A significant example of the sustainability of SMRs is the NuScale Power project, which has demonstrated the ability of small modular reactors to provide a flexible solution for decarbonizing energy grids, especially in isolated areas or regions with insufficiently diversified energy mixes. Functional SMR prototypes have already been successfully tested for industrial and commercial purposes, proving their long-term viability.

Furthermore, if SMRs are implemented on a large scale, they can contribute to the creation of jobs in the energy sector, and the technologies associated with them can stimulate technological innovation in related industries, such as the production of nuclear fuels and recyclable waste. These economic and technological advantages will facilitate the integration of SMRs into a diversified energy mix, thus contributing to global sustainability. The long-term sustainability of SMRs can be further enhanced through their integration into hybrid systems combining nuclear, renewable, and hydrogen-based technologies. Such configurations can provide both baseload and flexible generation capacity, effectively balancing intermittent renewable output while supplying clean hydrogen for industrial and transportation uses.

Future research should focus on optimizing these hybrid configurations by developing dynamic operation models that simulate the interaction between SMRs, renewable sources, and hydrogen production units under different load conditions. In addition, techno-economic analyses are needed to assess the cost-effectiveness and scalability of such systems in real-world scenarios.

Collaborative demonstration projects supported by governments, industry, and research institutions will be essential to validate these hybrid concepts and accelerate their commercial deployment. By combining proven nuclear reliability with the flexibility of renewable and hydrogen technologies, hybrid SMR systems could play a transformative role in achieving global decarbonization and long-term energy resilience.

6. Conclusions

In conclusion, small modular reactors (SMRs) offer an innovative solution for the global energy transition, significantly contributing to decarbonization and sustainability goals. Through lower construction costs, improved safety and flexibility, and the possibility of integrating with renewable energy sources, SMRs can ensure the stability of electricity grids and reduce carbon emissions.

These technologies represent an effective alternative for complementing renewable sources, compensating for their intermittency and ensuring a constant source of energy. In addition, through features such as off-site generation and passive safety designs, SMRs open up new perspectives for the development of a diversified and secure energy mix.

However, their implementation involves challenges related to high initial costs, public acceptance and complex regulations. Appropriate technological solutions and policies are essential to overcome these barriers and to support the integration of SMRs into global energy mixes.

Thus, SMRs can become a central pillar in the energy systems of the future, contributing to a sustainable transition, reducing emissions and strengthening global energy security.

The originality of this study lies in the conceptual proposal of a hybrid energy system that integrates SMRs with renewable sources and hydrogen production units. This approach provides an innovative framework for optimizing energy generation and storage, enhancing grid flexibility, and accelerating the transition toward a low-carbon and resilient global energy mix.

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