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Nuclear Small Reactors as a Key Solution in the Net-Zero Transition

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ABSTRACT

The ongoing transformation of the energy sector, driven by the global push for decarbonization, technological advancements, and energy security, positions small modular reactors (SMRs) as a pivotal innovation in the portfolio of energy enterprises. This study explores SMRs as a key sustainable development direction for energy companies aiming to meet stringent environmental goals while addressing growing energy demands. Various types of fuel such as LEU (Low-Enriched Uranium), HALEU (High-Assay Low-Enriched Uranium), TRISTO (Tri-Structural Isotropic), Molten Salt Fuel and MOX (Mixed Oxide Fuel) were also analyzed in terms of their properties and possibilities of use in SMRs. The research incorporates secondary data to examine the economic, environmental, and strategic implications of adopting SMRs. Insights are drawn from global case studies and industry reports, highlighting the potential for SMRs to enhance operational efficiency, reduce costs, and support the transition to a low-carbon economy. The study also identifies key challenges, including regulatory barriers, public acceptance, and technological readiness, that must be addressed to fully realize the potential of SMRs. the findings underscore the critical role of SMRs in enabling energy enterprises to achieve sustainability while maintaining competitiveness in an evolving energy landscape. Companies like Rolls-Royce SMR, NuScale Power, Rosatom, General Electric Hitachi, and Kairos Power are pushing the boundaries of technology by investing heavily in research and development initiatives. This research contributes to a deeper understanding of how SMRs can serve as a corner-stone of innovation and adaptability in the energy sector, paving the way for resilient and sustainable energy systems in the future.

Keywords: energy sector, small modular reactor, zero net emission, energy enterprise development, environment, climate protection

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1. INTRODUCTION

Given the ambitious global targets for reducing greenhouse gas emissions, transforming the energy sector toward zero emissions necessitates a wide range of actions. It is also essential to specify the kind of net-zero emissions countries aim to achieve, as this can vary depending on national priorities, technological capabilities, and policy frameworks. Considering the critical role of energy-related emissions in driving climate change, transitioning to clean energy sources—such as nuclear, hydro, solar, and wind—is fundamental for countries seeking to decarbonize their economies and mitigate environmental degradation (Rogelj et al, 2021; Kartal et al., 2025). For instance, some countries may focus on achieving net-zero emissions by emphasizing renewable energy sources, while others may incorporate nuclear energy solutions, such as small modular reactors (SMRs), as part of a broader, more diversified strategy. Defining the specific pathways and targets for zero emissions allows for a clearer roadmap and more targeted actions that align with each country's unique context and capabilities. Small modular reactors (SMRs) are gaining increasing attention alongside the long-term operation of existing nuclear power plants and the construction of large-scale Generation III reactors, which are de-signed as successors to Generation II reactors. These reactors feature improved fuel technology, higher thermal efficiency, and enhanced safety systems, including passive nuclear safety, with the first Generation III reactors being built in Japan in the mid-1990s and several more currently under design in Europe (Owais, 2022). SMRs have the potential to play a pivotal role in delivering clean energy to sectors of the economy where emissions reduction is particularly challenging, such as heavy industry, transportation, and localized energy systems in remote areas (Liu et al., 2023).

SMRs offer not only flexibility and scalability but also the possibility of integration with existing energy systems, making them an attractive solution for local communities and countries with limited financial resources. With lower infrastructure requirements and reduced initial capital costs, SMRs can be deployed in regions where traditional large-scale reactors are impractical due to technical or financial constraints (IAEA, 2024).

Moreover, their modular design supports faster construction processes, enabling more rapid achievement of emission reduction targets. Integrating SMRs with innovative technologies, such as energy storage systems, can further enhance energy efficiency and grid stability (Poudel and Gokaraju, 2021; Michaelson and Jiang, 2021).

In light of these challenges and opportunities, conducting scientific research on SMRs becomes increasingly crucial. Such research helps identify technological, economic, and regulatory barriers that must be overcome for SMRs to reach their full potential. These studies can provide essential data to inform strategic decision-making by energy enterprises and governments, contributing to an effective and sustainable energy transformation worldwide.

The main objective of the research presented in the paper is to analyze the role of SMRs as a key element of the energy transformation towards zero carbon dioxide emissions. The paper focuses on the potential of SMRs to ensure energy stability while reducing greenhouse gas emissions, constituting an alternative to traditional energy sources such as coal or gas. Additionally, it discusses strategic aspects of implementing nuclear technologies in the context of climate change.

The paper fills a research gap regarding the application of SMR technologies in the global energy transformation. Previous analyses have focused mainly on large nuclear power plants, while this study draws attention to smaller, scalable units that can complement energy systems, especially in countries and regions with lower energy demand or limited infrastructure. Another novelty is the approach to assessing the possibilities of SMRs in the context of the development of energy markets and challenges related to the transformation towards carbon neutrality, taking into account not only technological aspects, but also political and economic ones.

The structure of the article begins with the Literature Review section analyzes existing studies on SMRs, considering their technological development, applications, and economic aspects. Next, the Materials and Methods section, which presents the research approach primarily based on the desk research method, utilizing available data sources to analyze the role of small modular reactors (SMRs) in the energy transition. The Results and Discussion section explores key aspects of small modular reactors (SMRs), beginning with their historical development and the motivations behind their emergence. It analyzes the economic viability of SMRs, their integration into power grids and industrial applications, and their role in decarbonizing energy-intensive sectors. The section also highlights major companies involved in SMR development and their technological advancements. Additionally, it examines the types of nuclear fuel used in SMRs, along with a comparison of SMRs and large nuclear reactors in terms of cost, safety, and operational flexibility. In the final section Conclusions, the most important findings are summarized, emphasizing the strategic significance of small modular reactors in achieving carbon neutrality. Key challenges related to technology scalability, policy frameworks, and market adoption are also discussed.

2. LITERATURE REVIEW

Small modular reactors are becoming an increasingly important solution in the context of global efforts to protect the environment and transition to a zero-emission economy. A review of several selected scientific papers on the development of these reactors and their industrial application allows us to understand the latest technological trends and innovations in this field. These articles focus on aspects such as energy efficiency, minimizing environmental impact, technological safety and integration of SMRs into existing energy systems. By analyzing these papers, it is possible to identify best practices, challenges and potential directions for further development of SMR technology.

The author conducted a literature review in the form of a table, which offers several advantages. Presenting the reviewed publications in a tabular format allows for a clear and structured comparison of key findings, technological trends, and innovations in the field of small modular reactors (SMRs). This approach enhances readability and facilitates the identification of best practices, challenges, and potential directions for further development. Additionally, the table format enables a quick assessment of the scope and focus of various studies, helping to highlight their contributions to energy efficiency, environmental impact reduction, technological safety, and integration of SMRs into existing energy systems. The table 1 presents selected publications that provide a cross-sectional view of the most important achievements and research in this rapidly developing field.

Table 1. Scientific paper dedicated SMRs aspects

Title of the scientific paper	**The most important aspects studied and presented in the paper**
Development aspects of small modular reactors – technical and infrastructural perspectives	
State-of-the-art review of small modular reactors.	Technological advances in nuclear power have the potential to replace fossil fuel-fired power plants as primary energy suppliers. A key element of the success of a nuclear power development program is a long-term energy policy, which requires continuous government support. According to the IAEA, small modular reactors can be classified according to various criteria, such as power, type of coolant, neutron energy and location. Such technological diversity of SMRs allows for their wide application, supporting the energy transformation and reducing greenhouse gas emissions (Vinoya et al., 2023).
Small modular reactors: Challenges and opportunities.	Small modular reactors are gaining popularity among industry and decision makers as a promising technology in the nuclear power sector. However, their widespread deployment poses a number of challenges, including technical, economic, regulatory and logistical. Strong support from governments and the development of effective mechanisms for international cooperation will be necessary to achieve this goal in the coming years (Vaya Soler, 2023).
Small modular reactors (SMRs) for producing nuclear energy: international developments.	Small modular reactors (SMRs) have been developed worldwide since the 1950s, when they were first successfully used in military marine propulsion systems. Recently, there has been a growing interest in SMRs from both designers and potential users. SMR designs are usually divided into categories based on the cooling technology used (Ingersoll, 2021).

Small modular and advanced nuclear reactors: A reality check.	Small modular nuclear reactors have been proposed as a potential solution to key challenges facing nuclear power technology. These challenges include economic competitiveness, accident risk, proliferation hazards, and radioactive waste production. It is important to carefully analyze the technical barriers to advanced reactor designs and prepare for the long-term commercialization process that could stretch over many years (Ramana, 2021).
Small modular reactor based hybrid energy system for electricity & district heating.	Hybrid power systems incorporating small modular reactors (SMRs) represent an innovative and fast-evolving technology that combines nuclear energy with renewable sources to create more sustainable energy solutions. These systems offer the potential to balance energy supply by leveraging the reliability of nuclear power alongside the variability of renewables like wind or solar. By integrating these technologies, hybrid systems can contribute significantly to reducing carbon emissions while enhancing the flexibility and resilience of modern energy grids (Poudel and Gokaraju, 2021).
Can small modular reactors help mitigate climate change?	Small modular reactors (SMRs) should be implemented into the economy as soon as possible to effectively address the challenges of climate change. However, their competitiveness in terms of time to mass implementation and costs still leaves much to be desired. The results of studies to date show that this process requires huge financial outlays and many years of work. Even official timelines indicate that the contribution of SMRs to decarbonization will be negligible before 2030 and will remain limited until 2035, even though the power grid should be almost completely decarbonized by then (Makhijani and Ramana, 2021).
Small Power Nuclear Plants: Technical Level and Prospects for Commercialization	Low-power nuclear power plants represent a promising solution for supplying stable, carbon-free energy to remote regions lacking developed infrastructure. Their versatility enables not only electricity generation but also centralized heat supply, water desalination, and hydrogen production. To enhance their competitiveness, it is essential to develop innovative reactor designs, optimize thermal circuit efficiency, use advanced coolants, and integrate small nuclear stations with gas turbines, energy storage systems, and hydrogen technologies to improve operational flexibility and economic performance (Kindra et al., 2024).
Economic and Social Perspectives on Small Modular Reactors	
Small modular reactors: A comprehensive overview of their economics and strategic aspects.	Small modular reactors (SMRs) are particularly well suited to scenarios where power requirements are in the range of 1-3 GWe. Their modular design and scalability make them an ideal choice for regions with growing energy demand or limited infrastructure for larger nuclear power plants. In addition, SMRs are aligned with policy objectives focused on economic development, as their implementation often involves local manufacturing, construction and maintenance activities. These projects contribute to job creation, both directly in the nuclear sector and indirectly through related supply chains. By addressing both the technical and social dimensions, SMRs provide a comprehensive solution to today's energy and policy challenges (Locatelli et al., 2014).
Economic potential and barriers of small modular reactors in Europe.	Achieving net zero emissions by 2050 would require nuclear power capacity to double between 2020 and 2050, largely due to low baseline emissions. Small modular reactors (SMRs) could play a key role in achieving this goal, offering flexible and scalable energy solutions. It is estimated that many of the first SMRs will be built and operational in the coming decade, which could revolutionize the energy sector. SMRs are used in various industries, such as electricity and heat generation, as well as in more specialized areas such as hydrogen production and seawater desalination. Their compact size and modular design enable installation in locations where traditional nuclear power plants would be uneconomical or difficult to implement. In addition, SMRs can support grid stabilization and integration with renewable energy sources, contributing to the decarbonization of the energy and industrial sectors on a global scale (Van Hee et al., 2024).
Potential for small and micro modular reactors to electrify developing regions.	Small-scale nuclear power, while often seen as a niche solution, has the potential to play a key role in addressing the huge energy gaps in developing countries. In particular, reactors in the 1 to 50 MWe range are technically suitable for meeting the energy needs of local communities and isolated areas that lack access to large power grids (L'Her et al., 2024).
Techno-economic analysis of advanced small modular nuclear reactors.	Small modular reactors (SMRs) offer significant development potential as a source of low-emission and reliable energy. This technology can not only replace fossil fuels, but also effectively support intermittent renewable sources. Moreover, nuclear energy generation requires much less space – about 75 times less than solar power plants and 360 times less than wind farms for a comparable amount of energy. However, ensuring the economic viability of building new reactors remains a key challenge (Asuega et al., 2023).

The research studies summarized in the table 1 illustrate that investigations into small modular reactors (SMRs) are being conducted systematically, addressing a broad spectrum of considerations beyond technical solutions. These studies also explore economic and environmental dimensions, reflecting a comprehensive approach to evaluating the potential of this technology. Such research is vital as it examines not only the feasibility of SMRs but also their long-term implications for energy markets and cli-mate objectives. By incorporating diverse perspectives, these studies play a key role in shaping policies and strategies to accelerate the integration of SMRs into sustainable energy systems.

3. MATERIALS AND METHODS

3.1 Research Method

The research method used to study small modular reactors (SMRs) was secondary research, also known as desk research. This methodology focuses on analyzing previously published materials to build a thorough and detailed understanding of the subject. Using readily available data, desk research facilitates effective exploration of the subject using credible sources such as scientific papers, industry publications, government reports, and statistical records.

The desk research method is widely used in science, especially in the initial stages of research, when the goal is to identify existing knowledge, analyze trends, and identify research gaps. Its use saves time and resources, while at the same time providing reliable, verified information. In the context of SMR research, where access to empirical data may be limited due to the novelty of the technology and information restrictions, desk research is an adequate and effective tool for conducting in-depth analysis (Chu and Ke, 2017).

3.2. Data Collection

In order to confirm the validity of the research findings, only the most credible and authoritative sources were included in the analysis. These sources, often from high-impact international journals, reflect the latest scientific developments and professional standards in the field. Rigorous selection criteria ensure that the findings are based on accurate and up-to-date evidence, increasing the credibility of the conclusions drawn from the study (Moore, 2006).

Desk research therefore enabled the analysis of publications published in reputable international journals, issued by well-known publishers such as Springer and Elsevier, as well as industry reports on the issue of SMRs. The analysis included a review of the latest research results on the technology, economics and implementation of small modular reactors, as well as their potential role in the energy transition. Documents from international organizations such as the IAEA (International Atomic Energy Agency) and the WNA (World Nuclear Agency) were taken into account, which provide comprehensive information on the prospects for the development of SMRs in different countries.

The latest online publications on SMR solutions were also analyzed, which were a valuable complement to traditional scientific sources. Websites, especially those run by research institutions, technology companies and industry organizations, proved to be a valuable source of information, as they often present the latest achievements, prototypes and trends even before they are formally described in the scientific literature. This made it possible to capture the current state of development of SMR technologies and to better understand their practical application in the dynamically changing energy context. The idea of desk research method is presented on the Figure 1.

Figure 1. Idea of the research methodology

Figure 1. Idea of the research methodology

Source: Author's own elaboration

A notable advantage of desk research is its ability to provide access to a vast range of data in a cost-effective and time-efficient manner. Unlike primary data collection, this method allows researchers to extract relevant information from existing literature, saving financial resources while maintaining depth and breadth of analysis. This efficiency is particularly advantageous for SMR studies, given the extensive documentation available on technological progress, market dynamics, policy frameworks, and environmental considerations associated with this innovative technology.

Furthermore, desk research facilitates the detailed examination of critical SMR attributes such as size, capacity, cost-efficiency, and safety measures. It enables researchers to perform comparative analyses of international practices, assess pilot projects, and evaluate global strategies for the integration of SMRs into modern energy systems. By synthesizing data from diverse sources, the method provides valuable insights into best practices and innovative approaches tailored to different energy markets and regional contexts (Bassot, 2022).

One of the key advantages of desk research is its ability to identify major trends and challenges, which, in the context of this study, provides a broad perspective on the role of SMRs in the energy transition. The analysis of available sources has made it possible to observe the efforts undertaken to develop SMRs within the framework of global initiatives for carbon neutrality and the adoption of clean energy technologies. Their potential contribution to addressing key energy challenges has been recognized. This approach highlights SMRs as a versatile solution that not only enhances energy security but also minimizes environmental impact.

The adaptability of desk research is another key strength, allowing for the continual integration of newly published studies and datasets into the analysis. This dynamic feature ensures that research remains relevant and aligned with the latest advancements, which is particularly critical in rapidly evolving industries like nuclear energy, including SMR, and sustainability. By staying updated, researcher involved in SMR was able to refine their findings and recommendations, ensuring they reflect the current state of knowledge in the field (Petti et al., 2018).

As a robust and systematic research methodology, desk research is recognized for its capacity to consolidate diverse perspectives and produce well-rounded conclusions. It enabled researcher to explore the interplay between technical, economic, and environmental dimensions, fostering a comprehensive understanding of the multifaceted nature of SMRs. This method is widely employed across various scientific disciplines, ranging from engineering to policy studies, underscoring its versatility and effective-ness.

In the context of SMRs, desk research not only supports the evaluation of existing knowledge but also contributes to the development of strategic recommendations that align with global energy transition goals. By analyzing documented case studies, examining pilot initiatives, and reviewing policy implications, researchers can identify gaps and opportunities that drive innovation and informed decision-making. The structured, evidence-based nature of desk research ensures that it remains a cornerstone of academic and applied inquiry, fostering progress in the development of advanced energy systems (Benson et al., 2016).

Moreover, desk research emphasizes critical analysis and selective use of high-quality information, reinforcing its credibility as a scientific tool. By adhering to stringent methodological principles, researchers can ensure that their conclusions are both reliable and actionable. This approach plays a crucial role in shaping effective policies, identifying scalable solutions, and supporting the adoption of SMRs as a key component in achieving a sustainable and low-carbon energy future.

4. EMPIRICAL RESULTS AND DISCUSSION

Energy companies have begun pursuing small-scale nuclear power as a key part of the future energy mix. Small modular reactors offer a promising alternative to traditional large nuclear reactors, offering flexibility, lower construction costs, and faster project turnaround times (Soler 2024). Smaller than traditional nuclear reactors, SMRs offer lower initial capital investment and improved safety features. SMRs are designed to be modular, allowing components to be manufactured in factories and assembled on site.

This modular approach also enables scalability, allowing additional SMR units to be added incrementally to meet rising energy demands. Increasingly, energy companies are investing in the development and implementation of SMRs, recognizing their potential to stabilize energy grids and complement renewable energy sources, which are characterized by variable production. An example is Dominion Energy, an electricity provider serving over 3.6 million customers in Virginia, North Carolina, and South Carolina. Dominion Energy, in collaboration with Amazon, is undertaking research and development efforts on small modular nuclear reactors. These reactors are set to play a pivotal role in positioning Virginia as a leading hub for nuclear innovation. The partnership between Dominion Energy and Amazon underscores their commitment to exploring innovative ways to accelerate SMR development and funding, while mitigating potential costs and risks for customers and capital providers (Dominion Energy, 2024).

Small modular reactors are gaining attention as a viable solution to complement power generation in national electricity systems. With a capacity of up to 300 MWe—compared to over 1,000 MWe for traditional nuclear plants—SMRs offer versatile applications due to their smaller size and lower capital requirements. This makes SMRs a valuable alternative to large-scale industrial energy systems (Tan et al., 2023).

By incorporating SMRs into their portfolios, energy companies support global CO2 emission reduction goals and accelerate the transition to a net-zero economy. The development of small modular nuclear energy represents a strategic step towards ensuring energy security and sustainable growth.

4.1 Economic aspects of SMR

Small modular reactors (SMRs) offer a number of significant economic and operational benefits over traditional, large-scale nuclear reactors. One of the main ad-vantages of SMRs is a significantly shorter construction schedule, resulting from their smaller scale, lower level of complexity, and different investment implementation methodology. Unlike large nuclear power plants, which require extensive on-site construction, complex technical systems, and lengthy regulatory processes, SMRs are de-signed for prefabrication and modular construction. This allows for the production of components in controlled factory conditions and their transport to the installation site, which significantly reduces costs and the risk of delays related to supply chain disruptions or other unforeseen issues. A comparison of costs between SMRs and conventional nuclear power plants is presented in Table 2.

Table 2. Comparison of construction costs and time of SMRs and large nuclear power plants.

Type of Reactor	Total Cost [USD]	Cost per 1 MW [USD]	Construction Time	Comments
Small Modular Reactor	50 million – 3 billion	5 million – 10 million	3-5 years	Lower installed capacities lead to higher unit costs per megawatt. Nevertheless, SMRs provide advantages such as faster construction timelines, modular design, and the potential for reduced operational expenses. As production scales up and more experience is gained in building these reactors, overall costs are expected to decline.
Large Nuclear	25 billion – 30 billion	3 million- 5 million	10-15 years	The cost range is consistent with international designs for large nuclear power plants, varying by region and specific design. Large nuclear power plants require significant transmission infrastructure to support their high efficiency and continuous operation. Key components include high-voltage transmission lines (typically 400–750 kV) that reduce energy losses over long distances, and transformer stations that regulate voltage levels for integration with the electrical grid.

Source: Author's elaboration based on Van Hee et al. (2024), Zhan et al., (2021) and Borowski (2025).

As a result, SMRs offer lower investment risk – their lower initial cost and the possibility of phased construction (module by module) make them more affordable and flexible in planning. Additionally, standardization of designs may translate into simplified licensing and regulatory processes in the future, which further reduces costs and speeds up technology implementation. All these features make SMRs an attractive option for countries and investors looking for efficient, scalable and less capital intensive nuclear energy solutions.

4.2. Use of energy from SMR in power networks and industry

SMRs can play a significant role in supporting the management of power grids, not only by stabilizing them and reducing the risk of overloads or failures, but also thanks to their unique design features that allow them to operate in emergency conditions. One of the key features is the ability to black start, i.e. start a unit from a so-called cold state - without the need to use an external power source. This means that the reactor can start generating electricity completely autonomously, even in the event of a complete power outage in the network.

The black start function is fundamental in emergency situations, such as extensive blackouts, when the main power sources fail and the system requires gradual and controlled restoration of operation. In such cases, the ability to start the SMR independently allows not only the reactor itself to be started, but also to power other units in the power system, enabling the so-called cascade start.

An example of a technology with such capabilities is the SMR project developed by NuScale, the design of which was designed to be completely independent from ex-ternal power at critical moments (Welter et al., 2023). In practice, this means that the reactor can function as a local energy source supporting the reconstruction of the power grid by stabilising the voltage, frequency and other system parameters necessary to restore the continuity of electricity supply (Boudot et al., 2022; US DoE, 2025; APPA, 2025). In addition, SMRs enable decentralized energy generation, which reduces transmission losses. They complement renewable energy sources by providing continuous power supply, support energy storage systems, enable flexible and scalable implementation of additional units, and increase system stability through advanced safety functions. Their large-scale introduction to the energy mix will contribute to reducing CO2 emissions, which will support climate and ecological goals. SMRs can effectively cooperate with renewable energy sources, providing a stable source of energy that compensates for the variability of energy production from RES, which increases the stability and reliability of the entire energy system. The construction time of SMRs is much shorter compared to large nuclear reactors, which speeds up the implementation process and reduces investment costs. Modern SMRs are designed with the highest safety standards in mind, often having passive safety systems that minimize the risk of failure.

Small Modular Reactors have significant potential to revolutionize energy and industrial processes by providing reliable and efficient process heat for critical applications. One of their key advantages is their ability to supply district heating for urban areas, effectively replacing traditional fossil fuel-based systems and contributing to significant reductions in greenhouse gas emissions. Additionally, SMRs can be utilized for industrial heating processes, such as in chemical production, food processing, or paper manufacturing, where consistent and high-temperature heat is required. They can also support agricultural applications, including greenhouse heating, providing a sustainable energy source to enhance productivity while minimizing environmental impact (Vanatta et al., 2023). The scheme of SMR used in the heating process is shown in Figure 2.

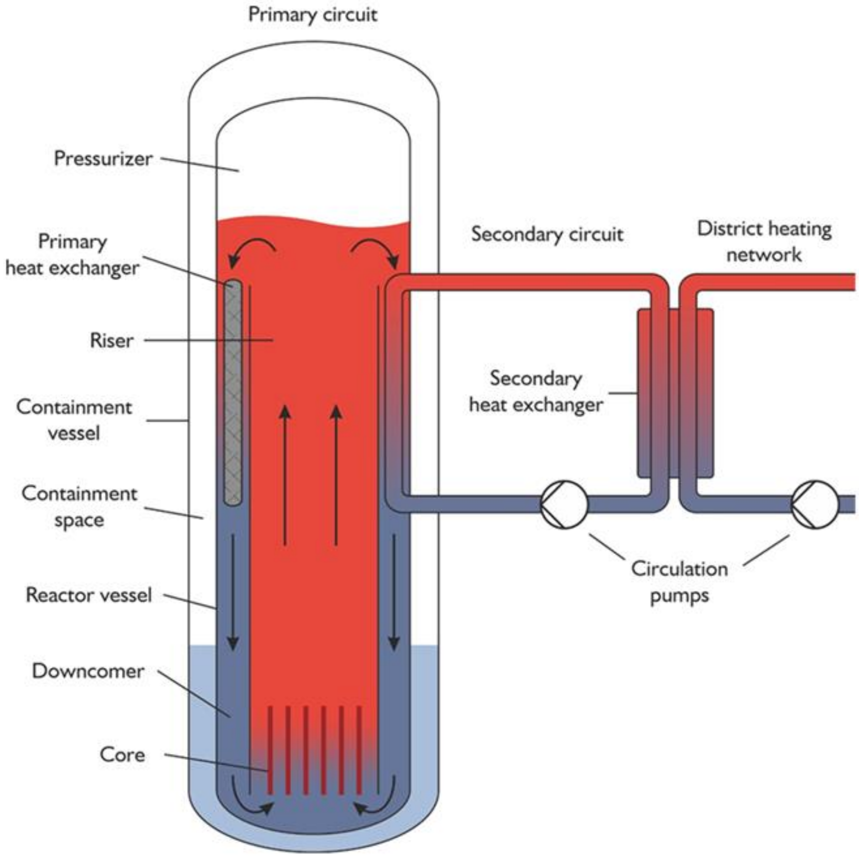

Figure 2. Scheme of LDR model.

Source: Komu and Tuominen (2023).

A single LDR-50 (Low-temperature District heating Reactor) can meet the heating needs of a small and medium cities such Kuopio, Espoo and Lahti, effectively replacing fossil fuel-based heating systems (NEA, 2024). Additionally, these units are designed to support production plants, enabling the production of fresh water or steam for industrial purposes. By reducing reliance on fossil fuels and promoting cleaner energy solutions, the LDR-50 also contributes significantly to cli-mate protection and the reduction of greenhouse gas emissions.

In addition to electricity generation, SMRs can play a transformative role in industrial operations, supporting seawater desalination, hydrogen production, and other essential processes (Nucleo, 2025; Ishaq and Dincer, Borowski, 2025). SMR process heat refers to the thermal energy produced by Small Modular Reactors, which can be harnessed for industrial processes requiring heat. Their versatility positions them as a key solution for driving the decarbonization of hard-to-abate sectors, such as transportation, chemical manufacturing, steel production, and heating (EIA, 2024; Daigle et al., 2024). By integrating SMRs into these industries, we can achieve substantial reductions in greenhouse gas emissions, enhance energy resilience, and accelerate the transition to a cleaner, more sustainable future. An example of the use of SMRs in various industries e.g. hydrogen production is shown in Figure 3.

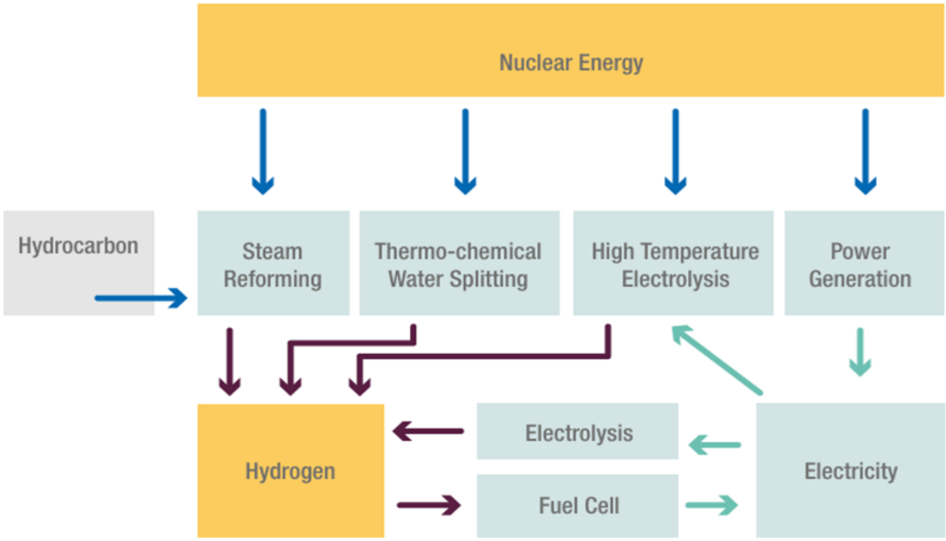

Figure 3. Scheme of nuclear energy used of hydrogen production.

Source: IAEA, (2024a)

The use of SMRs, as shown in Figures 2 for heating and Figure 3 for hydrogen production, demonstrates their increased versatility and utility, making them a valuable part of today's energy system. SMRs can improve an industrial facility's carbon footprint because nuclear power is a low-carbon energy source. Furthermore, nuclear power is reliable and non-intermittent (PEI, 2024; Borowski 2025a). SMRs are an important complement to large nuclear reactors, collectively contributing to a more flexible, reliable, and environmentally friendly energy system, which is key to accelerating the transition to a zero-emission economy.

4.3. Companies involved in the production of SMRs

The emission reduction target can be achieved through a combination of long-term operation of existing nuclear power plants, new large-scale facilities and SMRs (Nriezedi-Anejionu, 2024). The role of nuclear power in achieving net zero emissions is key. SMRs are expected to play an increasingly important role in harnessing nuclear power to meet emissions targets, while also having the potential to alleviate energy poverty and promote economic development and prosperity. An example of the use of a micro-modular reactor to provide power in remote locations is the portable Westing-house eVinci® Micro-Reactor, a very small modular reactor (vSMR). This reactor provides combined heat and power from 200 kW(e) to 15 MW(e). The design of this reactor allows for full factory construction, fueling and assembly with an expected life of 10 years. The intended use of the eVinci micro-reactor is to produce clean, safe and cost-competitive heat and power for remote communities, mines and military installations (IAEA, 2024b).

SMRs will become an increasingly popular source of reliable, low-carbon power and heat generation for sectors where emissions reduction is difficult. There is a market demand for SMRs to power baseload grids to replace coal-fired power generation, as well as in other sectors of the economy (OECD, 2025).

Energy companies are working with governments, research institutions and technology providers to advance SMR technologies. Collaboration is essential between stakeholders, including project promoters, financial institutions, regulators, researchers, training institutions, civil society organisations and policy makers. Pilot projects and demonstration plants are being established around the world to validate designs, optimise operations and ensure regulatory compliance. Research into SMR development and deployment is increasingly underway in many countries including the Unit-ed States, Republic of Korea, Russia, China, Argentina, Japan, the United Kingdom and Canada. In order to be introduced to the market, SMR devices must be licensed by the nuclear safety authorities of the countries where they will be used, and production should be carried out in a serial manner to reduce production costs (Small Modular Reactors, 2025).

The small modular reactor (SMR) market is characterized by the presence of several key players, including established nuclear technology companies and innovative startups, which play a pivotal role in the development and commercialization of these cutting-edge technologies. Companies such as Rolls-Royce SMR, NuScale Power, Rosatom, General Electric Hitachi, and Kairos Power are recognized leaders in this field, continuously driving advancements through intensive research and development efforts. Their innovative approaches encompass groundbreaking reactor designs, enhanced safety mechanisms, and modular construction techniques aimed at reducing costs and deployment timelines (Emergen, 2020).

These companies are not only focused on the technical aspects of reactor design and construction but are also actively engaged in fostering collaborations with international organizations, local governments, and industry stakeholders. Such partnerships facilitate the creation of robust frameworks for regulatory compliance, supply chain optimization, and public acceptance, ensuring the safe and efficient integration of SMRs into diverse energy systems.

Furthermore, these enterprises are at the forefront of implementing pioneering solutions, such as hybrid energy systems that combine SMRs with renewable energy sources, and advanced digital tools for monitoring and maintaining reactor performance. This relentless focus on innovation underscores their commitment to addressing the complex challenges of transitioning to a low-carbon energy future (Amin et al., 2024).

A list of selected companies involved in projects related to the development and implementation of SMRs is presented in Table 3, showcasing the breadth and diversity of efforts within this trans-formative sector.

Table 3. Selected Companies Involved in SMR Production.

Name of the company	Name of SMR reactor	Country
NuScale	NuScale Power Module	United States
Kairos Power	KP-FHR	United States
GE Hitachi Nuclear Energy	BWRX-300	United States
Ultra Safe Nuclear Corporation	Micro-Modular Reactor (MMR)	United States
TerraPower	Natrium	United States
X-energy	Xe-100	United States
General Atomics	Energy Multiplier Module	United States
Idaho National Laboratory	The 4S (Super-Safe, Small and Simple) Reactor and the ARC-100	United States
Westinghouse Electric Company	eVinci Micro Reactor	United States
Holtec International	SMR-160	United States
Oklo	Aurora	United States
Rolls-Royce SMR	Rolls-Royce SMR	United Kingdom
Rosatom	KLT-40S	Russia
OKBM Afrikantov	VBER-300	Russia
Canadian Nuclear Laboratories	Advanced Fuel CANDU Reactor (AFCR)	Canada
Moltex Energy	Stable Salt Reactor (SSR)	Canada
U-Battery Developments	U-Battery	United Kingdom, Netherlands, Germany
Korea Atomic Energy Research Institute	SMART	Korea
Seaborg Technologies	Compact Molten Salt Reactor (CMSR)	Denmark
China National Nuclear Corporation	HTR-PM and NHR-200	China
ThorCon Power	ThorCon Isotope Power System (TIPS) and ThorCon Molten Salt Reactor (TMSR)	United Arab Emirates

Source: Author's elaboration based on OECD (2025), Small Modular Reactors (2025) and M&M (2025).

The data presented in the Table 3 regarding companies investing in SMRs technologies and the countries where pilot projects are being implemented shows that interest in this solution is global and growing rapidly. SMRs are attracting attention as a promising source of clean, scalable and reliable energy, especially in the context of global efforts to decarbonize the energy sector. Companies such as Dominion Energy in the United States are working on pilot solutions that aim to test the effectiveness of the technology in real-world conditions and obtain certification of compliance with regulations. Companies such as X-energy and Energy Northwest are implementing projects that are to generate several hundred megawatts of power from SMRs, while optimizing operational processes and adapting the technology to market requirements. In many countries, such as Canada, the United Kingdom and South Ko-rea, investments are being made that serve as platforms for testing new technologies. Such activities al-low companies to verify technical assumptions, develop business models and better prepare for wide commercialization. The involvement of companies in the development of SMRs is driven by the potential economic, technological and environmental benefits offered by this innovative form of nuclear energy.

4.4. The beginnings and further development of small-scale nuclear power generation

The increasing share of renewable energy significantly impacts grid operations. Solar panels generate variable energy depending on geographical location and season, while wind energy production is subject to seasonal and daily weather conditions.

The origins of small nuclear power generation can be traced back to research projects from the 1950s and 1960s. The technology that underpins small modular reactors (SMRs) has been in use since the mid-1950s, initially as a power source in sub-marines, and since the 1960s, as an energy source for American radar stations and Arctic facilities (Ingersoll, 2021). The United States Navy's development of the USS Nautilus, the world's first nuclear-powered submarine, marked a significant milestone in the use of small-scale nuclear reactors. These reactors were compact, efficient, and suitable for confined spaces, which laid the foundation for the concept of modular reactors. Thanks to advancements in science and engineering, SMRs have become a viable alternative to traditional nuclear power plants. In the 1960s, the U.S. began to explore the application of similar technologies for land-based energy production. The Westinghouse Electric Corporation and other companies initiated early designs for small reactors, primarily aimed at remote and off-grid locations (Westinghouse 2024). Small nuclear power generation, based on modular reactors, is now an innovative branch of the energy sector that is gaining increasing global attention. It encompasses the design, construction, and operation of nuclear reactors with much smaller capacities than traditional nuclear power plants.

The development of the SMR industry is becoming a key factor in shaping the future of energy, particularly in light of the growing challenges related to energy security, climate change, and sustainable development (Cooper, 2014). SMRs have proven to be a promising technological advancement in the nuclear energy sector, with potential ap-plications in addressing energy challenges and supporting sustainable growth. These small modular reactors represent a modern solution in nuclear energy, gaining popularity due to their unique features and advantages.

While they do not directly compete with large-scale reactors, which remain the backbone of the energy system, SMRs serve as a complementary solution. SMRs are highly flexible in application, allowing for installation in areas where building large reactors would be impossible or economically unfeasible, such as remote regions, islands, or areas with limited energy infrastructure. Due to their modular construction, SMRs can scale their output gradually as energy demand increases, which is especially beneficial for rapidly developing regions. The ability to install additional identical units at a single location significantly reduces the financial burden of investment and allows for adjustment to local energy demand (Schlegel and Bhowmik , 2024).

Small modular reactors (SMRs) can use a variety of nuclear fuels, depending on their design and the technology used to manufacture the reactor. SMRs are designed for greater efficiency, safety, and flexibility of deployment. The table below lists the different types of reactors and the fuels they use, emphasizing the diversity of SMR technologies. Each fuel type is carefully selected to meet the reactor's operational requirements, fuel cycle sustainability, and safety considerations. This diversity allows SMRs to serve a wide range of applications, from power generation to industrial heat production, and even exploration in vessels or spacecraft. The table 4 lists the different fuel types, their characteristics, and the types of reactors in which they are used.

Table 4. Type of nuclear fuel, its properties and applications

Type of fuel	Properties of fuel used	Type of reactors	Examples
Low-Enriched Uranium (LEU) Fuel (<5% U-235)	Used in conventional SMRs that follow existing LWR technology due to its compatibility with existing nuclear infrastructure and compliance with non-proliferation regulations.	Light Water Reactors (LWRs), including Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs)	NuScale (PWR), SMART (PWR), CAREM (PWR)
High-Assay Low-Enriched Uranium (HALEU) Fuel (5–20% U-235)	Provides higher efficiency and longer fuel cycles, allowing for extended operation without refueling	It is essential for advanced SMRs, including fast reactors, high-temperature gas-cooled reactors (HTGRs), and select molten salt reactors (MSRs), due to its higher fissile content and improved neutron economy	TerraPower's Natrium (Sodium-Cooled Fast Reactor), X-energy's Xe-100 (HTGR), Kairos Power's KP-FHR (Fluoride-Salt-Cooled High-Temperature Reactor)
TRISO (Tristructural Isotropic) Fuel	Extremely robust fuel form with high thermal and radiation resistance, ideal for gas-cooled and high-temperature SMRs.	High-Temperature Gas-Cooled Reactors (HTGRs), Pebble-Bed Reactors (PBRs), and some Fluoride-Salt-Cooled High-Temperature Reactors (FHRs)	X-energy's Xe-100 (HTGR), Ultra Safe Nuclear Corporation's (USNC) MMR (Micro Modular Reactor), Kairos Power KP-FHR
Molten Salt Fuel (Liquid Fuel - Uranium/Thorium/ Plutonium in Fluoride/Chloride Salt)	Used in liquid-fueled SMRs, offering inherent safety features, high-temperature efficiency, and potential for fuel reprocessing.	Molten Salt Reactors (MSRs), including both thermal and fast-spectrum designs	Terrestrial Energy's IMSR (Integral Molten Salt Reactor), ThorCon (Thorium Molten Salt Reactor), Moltex SSR-W (Stable Salt Reactor)
Mixed Oxide (MOX) Fuel (Uranium-Plutonium Oxide)	MOX fuel is chosen for SMRs because it allows for the recycling of plutonium from spent nuclear fuel, reducing nuclear waste while increasing fuel sustainability. It also provides comparable or higher energy output than conventional uranium fuel, making it a viable alternative for SMRs aiming for efficiency and sustainability.	Fast Neutron Reactors (FNRs), Sodium-Cooled Fast Reactors (SFRs), and some Gas-Cooled Fast Reactors (GFRs)	TerraPower's Natrium (SFR), ARC-100 (SFR), PRISM (SFR)
Thorium-Based Fuel (Thorium-Uranium Cycle, Thorium-Plutonium Cycle)	Thorium-based fuels are attractive for SMRs due to their superior fuel sustainability, high natural abundance, and enhanced safety features. Their ability to produce less long-lived nuclear waste and higher proliferation resistance makes them a strong candidate for next-generation reactors	Molten Salt Reactors (MSRs), High-Temperature Gas-Cooled Reactors (HTGRs), and Heavy Water Reactors (HWRs)	Remote and Off-Grid Power Generation and Industrial and Process Heat Applications

Source: Author's elaboration based on Brown et al. (2017), Zohuri and McDaniel (2019), Hussein (2020), Lee et al. (2015), Fernández-Arias et al. (2023).

Given the current global energy landscape and nuclear regulations, fuels with uranium enrichment levels below 5% (commonly referred to as low-enriched uranium, LEU) have promising application prospects. LEU is widely used in commercial nuclear reactors due to its compliance with international non-proliferation agreements and a well-established supply chain. The use of LEU minimizes the risk of nuclear proliferation while ensuring efficient and reliable energy production. Additionally, many advanced small modular reactors (SMRs) are designed to operate with LEU fuel, making them more viable for short-term deployment. The regulatory framework in many countries favors reactors using uranium enrichment levels below 5% since they are compatible with existing fuel handling and waste management protocols. Further-more, advancements in fuel technology continue to enhance the efficiency and lifespan of LEU fuel, making it a practical choice for the future of nuclear power generation.

An alternative solution could be the introduction of high-assay low-enriched uranium (HALEU) fuel, which has an enrichment level of 5–20% 235U. HALEU offers a higher uranium content while maintaining low enrichment, with the goal of increasing reactor efficiency, thereby reducing fuel delivery costs and lowering the levelized cost of electricity (LCOE). While reducing LCOE presents a clear advantage, increasing enrichment to HALEU levels in SMR or microreactor designs may introduce several challenges, including regulatory hurdles, supply chain limitations, and potential proliferation concerns [Lee, 2015; Carlson et al., 2022]. The NRC will license the commercial production, utilization, storage, and transportation of HALEU and HALEU-containing fuel. Addressing this aspect will help ensure a more comprehensive and policy-relevant analysis of the deployment pote.tial of SMRs (US NRC, 2025).

Growing investments in SMRs indicate their key role in the energy transition, and pilot projects and demonstration plants are a necessary step towards large-scale deployment of these technologies (Carlson et al., 2022; Lee et al., 2015; Kartal et al., 2025). The unit cost of energy production in large nuclear reactors versus SMRs varies significantly depending on several factors, including the specific design, location, and scale of deployment. However, general trends can be observed, as shown in the Table 5.

Table 5. Comparison of the attributes of large nuclear reactors and SMRs.

Aspect	Large Nuclear Reactor	Small Modular Reactors
Economy of Scale vs. Modular Construction	Economy of Scale - Large reactors benefit from economies of scale, potentially reducing the cost per megawatt-hour (MWh) once operational.	Modular Construction - SMRs are designed for modular construction, which can reduce time and costs through factory production and on-site assembly.
Capital Costs	Large reactors typically require substantial initial investments due to their size and complexity.	Smaller-scale projects require lower initial investments compared to large reactors.
Unit Cost	The average Levelized Cost of Electricity (LCOE) for large reactors is typically between $80 and $100 per MWh, varying by project specifics.	LCOE estimates for SMRs range from $60 to $110 per MWh. Initial costs may be higher but are expected to decrease as the technology matures and production scales up.

Source: Author's elaboration based on Pannier and Skoda (2014), Nøland et al. (2025).

A comparison of large nuclear reactors and small modular reactors (SMRs) high-lights their distinct advantages and suitability for different energy needs. Large reactors leverage economies of scale to reduce the cost per megawatt-hour (MWh) over time, making them ideal for large, centralized power generation. However, SMRs, with their modular design, offer greater flexibility, lower initial capital investment, and faster construction times. These features make SMRs particularly attractive for smaller-scale energy solutions, especially in regions with limited infrastructure or where rapid deployment is essential.

A more detailed analysis of these technologies allows for a deeper understanding of the various categories, such as capital costs, operating efficiency, and scalability. By examining the specific advantages of each reactor type across multiple dimensions, we can better assess their roles in the future energy landscape and determine how they align with global sustainability goals. The following Table 6 provides a more precise comparison of the key aspects of large nuclear reactors and SMRs.

Table 6. Comparison of Key Factors Influencing the Design and Performance of Large and Small Modular Nuclear Reactors

Category	Large Nuclear Reactors (LNRs)	Small Modular Reactors (SMRs)
Scale of Construction	Large-scale, complex construction requiring substantial infrastructure	Small, modular units that can be built in factories and assembled on-site.
Construction Time	Typically 5–7 years or more due to the large size and regulatory complexity.	Shorter construction times, around 3–5 years, due to modularity and pre-fabrication.
Location Suitability	Requires a large and stable site, require specific geographical conditions, often near large water bodies for cooling.	Can be deployed in a variety of locations, including remote areas, due to their smaller size and modular nature.
Flexibility	Limited flexibility; the plant's size and infrastructure are typically fixed once construction starts.	High flexibility; multiple units can be added incrementally to meet growing demand.
Technology & Design	Based on traditional nuclear reactor technology with complex designs, requiring significant infrastructure and expertise.	Designed with modularity in mind, these systems are more flexible, scalable, and adaptable to diverse environments. They often incorporate state-of-the-art technologies, including advanced reactor designs, to enhance performance and safety
Power Output	Large reactors generate between 1,000 MW and 1,600 MW per unit.	SMRs typically produce between 50 MW and 300 MW per unit, with the possibility of combining multiple units.
Safety and Regulatory Compliance	Large reactors must meet rigorous safety standards and regulatory approvals, often facing delays.	SMRs are designed with enhanced safety features, including passive safety systems, and are often seen as easier to license and regulate due to their smaller size and simpler designs
Market Adoption	Large reactors dominate the energy markets in countries with developed nuclear infrastructure	SMRs are seen as a disruptive innovation, with increasing interest from smaller utilities, emerging economies, and industries seeking decentralized energy solutions
Environmental Impact	Large reactors have significant environmental impacts in terms of land use and waste management.	SMRs produce lower amounts of waste and have the potential to integrate with other low-carbon energy sources, offering a more sustainable approach to nuclear energy.

Source: Author's elaboration based on the data drawn from a variety of industry reports, including sources from WNA (2025) ONE (2025), SMR (2025), Rahman et al. (2023) and Mancini (2009).

The Table 6 compares large nuclear reactors and small modular reactors (SMRs) across key aspects such as cost, flexibility, safety, and environmental impact. It highlights SMRs' advantages, including lower initial investment, faster construction, and greater deployment flexibility, while also acknowledging the established benefits of large reactors, such as economies of scale and high operational efficiency.

The comparison reveals the strengths and limitations of each reactor type, offering insight into how SMRs can provide more flexible and economical solutions for future power generation compared to traditional large-scale reactors. Large reactors, while benefiting from economies of scale that reduce the cost per megawatt-hour (MWh) once operational, require significant upfront capital and lengthy construction periods. Conversely, SMRs are designed with a modular approach, allowing for reduced construction times and lower initial costs, making them a more accessible and adaptable option for smaller utilities or regions with lower electricity demands (Budnitz, 2018).

The comparison presented in the table allows you to see the advantages and dis-advantages of each of the two basic groups of reactors, and to better understand how SMRs can provide more flexible and economical solutions for power generation in the future compared to traditional large-scale nuclear reactors. While large reactors benefit from economies of scale, reducing the cost per megawatt-hour (MWh) once operational, they require substantial initial capital investment and longer construction time-lines. In contrast, SMRs offer a modular design that reduces construction times and capital expenditures, making them more accessible for smaller utilities or regions with lower electricity demand.

Additionally, the lower up-front costs of SMRs, combined with their scalability and reduced regulatory complexity, make them a more adaptable solution for a wide range of applications, including remote or off-grid locations, and regions with limited infrastructure. Although the levelized cost of electricity (LCOE) for SMRs may initially be higher than large reactors, the potential for cost reductions through technological advancements and increased manufacturing efficiency over time makes them an at-tractive long-term option. This flexibility and reduced risk profile are significant advantages as the energy sector transitions to cleaner, more decentralized energy systems (IAEA, 2024; Nøland et al., 2025; WNP, 2023).

As the industry progresses and SMR technologies mature, the overall cost gap between these two reactor types is expected to narrow, with SMRs potentially providing a competitive alternative for future nuclear power generation. In general, nuclear energy can contribute to affordability through systemic approaches, especially in systems with a large number of renewable energy sources and stringent carbon dioxide emission constraints. In this context, low-emission energy sources, such as nuclear and renewable energy, are becoming increasingly important as a response to the threats posed by climate change (Egieya et al., 2023, Ozcan et al., 2024).

According to the Valuates report from the year 2022, the global SMR market is projected to grow from $3.5 billion in 2020 to $18.8 billion by 2030, driven by rising demand for sustainable energy and greenhouse gas reductions. SMRs offer an energy-efficient, secure, and attractive option for countries and companies investing in the future of energy (Valuates, 2022).

Enterprises exploring innovative energy solutions can consider small modular reactors (SMRs) as a viable option. SMRs offer scalable, flexible, and cost-effective energy production, making them suitable for industries with significant energy demands. Their modular design allows easier deployment, even in remote or decentralized locations, while advanced safety features and lower initial investments reduce risks and barriers to adoption. By integrating SMRs, enterprises can enhance energy security, support sustainability goals, and contribute to the transition toward low-carbon operations.

Entrepreneurship in the field of small modular reactors (SMRs) represents a dynamic and strategic response to the evolving energy landscape (Vinoya et al., 2023). When planning investments, energy companies must consider several critical factors, including construction and operational costs, return on investment, and the competitive edge of SMRs compared to other energy sources like traditional nuclear plants, coal power stations, and renewable energy (Borowski 2024). SMRs, with their smaller size and capacity, are de-signed to meet niche energy demands, offering flexible energy production for diverse applications, including replacing aging fossil fuel plants, cogeneration in developing countries with small grids, and serving remote or off-grid areas. Additionally, their modular nature facilitates scalability, enabling tailored energy solutions for varying demands.

mostly mathematical description of the method (method or model) to be used in a theoretical or empirical analysis. Appropriate application based on the chosen method computer implementation using a software package.

5. CONCLUSION

The results of the conducted research highlight several key points:

First, SMRs represent a groundbreaking solution in nuclear energy, offering eco-nomic, technological, and social benefits. Their modular design enables mass production and shortens construction time, significantly accelerating the implementation of energy projects.

Second, SMRs demonstrate exceptional technological flexibility, allowing their application in various operational conditions. They can utilize different cooling methods, including water, high-temperature gas, liquid metal, and molten salt, making them adaptable to diverse environments and energy needs.

Third, SMRs can be deployed in locations with limited infrastructure and cooling water availability, expanding the reach of nuclear energy to previously underserved regions. This not only improves access to reliable power but also enhances energy supply security by minimizing transmission losses and reducing dependence on extensive power grid infrastructure.

Fourth, the development and deployment of SMRs bring significant economic benefits by creating jobs at multiple levels—from construction and operation to maintenance and safety monitoring. Their implementation in regions affected by coal plant closures helps retain highly skilled personnel within the energy sector, supporting local economies and long-term regional growth.

Fifth, SMR technology plays a crucial role in advancing research and development, engaging scientists and engineers in efforts to improve reactor efficiency and safety. This fosters technological innovation and contributes to the continuous progress of the energy industry, reinforcing the transition toward more sustainable and resilient energy solutions.

SMRs constitute a key component of the energy transition, combining sustainable development with economic viability. Their implementation not only addresses the global demand for clean energy but also supports technological and socio-economic progress, paving the way for a more resilient and environmentally friendly energy future.

The key findings of the study provide valuable insights for policymakers and energy market stakeholders, particularly in highlighting the growing significance of small modular reactors (SMRs) and the ongoing need for systematic research into their implementation. The research considered different SMR models, fuel types, and associated costs, emphasizing their potential role in the sustainable energy transition.

Further studies are necessary to unlock the full technological and economic potential of SMRs, with a focus on five main areas: (1) economic feasibility and cost re-duction through optimization of production and financing models; (2) evaluation of various fuel types, including HALEU and molten salt, for performance and flexibility; (3) integration with renewable energy to create hybrid, off-grid solutions; (4) development of clear regulatory and safety standards to support licensing and public acceptance; and (5) analysis of socio-economic impacts, especially in post-coal regions, including employment and local development. These directions will support the broader deployment of SMRs as a clean, scalable, and economically viable energy solution.

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