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Small Modular Reactors in the Energy Transition: Economic, Regulatory, and Technological Perspectives

Economic, Regulatory, and Technological Perspective

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Abstract **- There is an unprecedented need to expand the toolbox of solutions to boost the scalability of clean power and energy systems. Amid the urgent need to scale clean energy systems, nuclear power is gaining renewed attention as a vital tool in the global energy transition. This paper reviews the current state and potential of small modular reactors (SMRs)—a new class of nuclear technology offering lower power capacities (around 300 MW), modular construction, and enhanced flexibility. Both conventional light-water and next-generation advanced reactor designs are assessed in terms of their system integration value, ability to provide grid services, and economic potential. Unlike traditional large-scale reactors, SMRs aim to achieve cost competitiveness through modularity and mass production rather than economies of scale. However, challenges remain regarding their uncertain techno-economic performance. This paper addresses these challenges by offering a foundational cost analysis, including the use of learning curves to estimate future deployment costs. SMRs can operate as baseload or dispatchable resources and may be integrated with thermal energy storage and renewables to enhance grid flexibility. The study discusses their role in delivering firm, low-carbon energy, which is essential for achieving climate targets such as those set in the Paris Agreement. Historical examples, such as France and Sweden, demonstrate nuclear energy's success in decarbonization. The paper ultimately positions SMRs as a potentially disruptive innovation for clean energy systems. The advent of small modular reactors (SMRs) represents a transformative leap in nuclear technology. With their smaller size, modular construction, and safety features, SMRs address challenges faced by traditional reactors. However, these technological advancements pose significant regulatory challenges that must be addressed to ensure their safe and effective integration into the energy grid. This paper presents robust regulatory strategies essential for the deployment of SMRs. We also perform economic and sensitivity analysis on a notional SMR project to assess its feasibility, profitability, and long-term viability, pinpointing areas for cost optimization and determining the project's resilience to market trends and technological changes. Key findings highlight market demand as the most influential factor, with public acceptance, regulatory clarity, economic viability, and government support playing critical roles. The sensitivity analysis shows that SMRs could account for 3% to 9% of the energy market by 2050, with a base case of 4.5%, emphasizing the need for coordinated efforts among policymakers, industry stakeholders, and regulatory bodies. Technological maturity suggests current designs are viable, with future R&D focusing on market appeal and safety. By synthesizing these insights, the paper aims to guide regulatory authorities in facilitating informed decision-making, policy formulation, and the adoption of SMRs**

Keywords : Nuclear energy, light-water reactors (LWRs), small modular reactors (SMRs), Advanced modular reactors (AMRs), Power system integration, Techno-economic evaluation. Introduction (*Heading 1*)

I. INTRODUCTION

A. Rising Need for Cleaner Energy

The world is witnessing an increased pace of transition to sustainable energy sources. Nuclear technologies, especially Small Modular Reactors (SMRs), are poised to become reliable solutions with minimal emissions when in operation, thus offsetting the increasing demand for electricity driven by the growth of the electrification sector. Unlike the conventional approach, which involves the construction of massive power plants that require several years to complete and are inflexible in terms of capacity, SMRs are self-contained modules that deliver 300 MW of electricity in 3-4 years.

B. Proven Benefits and Future Pairings

Countries such as France and Sweden demonstrate the importance of nuclear, which provides power to 70% of their electricity grids, reducing CO2 emissions by 70-80% compared to fossil fuel-based power plants. SMRs take this further by being fully adaptable to variables such as solar panels or batteries, allowing for the creation of hybrid systems that can level out the ups and downs of renewable energy.

II. SMR TECHNOLOGY OVERVIEW

The planet is facing an ever-increasing demand for clean energy from electric cars, industries, and data centers, while simultaneously trying to meet the challenge of reducing carbon emissions under agreements such as the Paris Agreement. Small Modular Reactors (SMRs) fill the gap as smaller, cleaner nuclear power plants that are usually 300 MW or smaller, designed to be assembled in a "building block" fashion in factories, reducing construction time from over a decade to only 3-4 years for on-demand or baseload electricity.

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What Makes SMRs Special

While traditional reactors are enormous and have extremely high capital start-up costs and are inflexible, SMRs focus on factory-manufactured reactors for cost-effectiveness and safety features that use passive cooling systems that do not require power outages. Countries such as France and Sweden demonstrate the power of nuclear energy, which has traditionally enhanced 70-80% cleaner energy grids; SMRs take this a step further by combining solar farms or batteries to create more intelligent and robust energy systems that directly attack climate change.

A. Key Benefits and Examples

SMRs reduce construction periods to 3-4 years through modular factories, compared to giants taking a decade, and passive safety designs (requiring no pumps during emergencies) enhance reliability. Notable examples include the SMART (330 MW thermal power for energy or seawater desalination) design from South Korea, Westinghouse's 200 MW integral PWR based on AP1000 technology, and the 4S sodium-cooled reactor from Japan, operating for 10-30 years without refueling.

B. Core SMR Designs

There are different kinds of Small Modular Reactors (SMRs), mostly light-water reactors (LWRs) and advanced designs, all under 300 MW for easy manufacturing and scaling. LWRs such as NuScale's VOYGR SMRs employ conventional pressurized water cooling with uranium fuel, providing well-proven safety by natural circulation and underground configurations for up to 77 MW per module, scalable to 924 MW reactors. More advanced designs utilize gas (e.g., helium in X-energy's Xe-100), molten salts, or sodium, allowing for greater temperatures for electric power and process heat, such as hydrogen production.

C. Role of Nuclear Energy in Mitigating Climate Change.

Nuclear energy has an important role to play in the mitigation of climate change and the increasing demand for energy worldwide. To meet the Paris Agreement target of keeping global warming below 1.5°C, it is necessary to cut greenhouse gas emissions drastically. The International Energy Agency (IEA) has identified nuclear energy as an important element in the achievement of a net-zero carbon future. Without nuclear energy, the cost of meeting deep decarbonization targets will rise substantially, as pointed out by the MIT Energy Initiative. The success stories of France and Sweden show that nuclear energy can facilitate rapid decarbonization of the power sector. Therefore, nuclear energy is not only a long-term solution to climate change but also a mature technology with decades of successful experience worldwide.

D. Emergence and Benefits of Small Modular Reactors (SMRs)Small Modular Reactors (SMRs).

SMRs are a significant technological breakthrough in the nuclear sector. Unlike conventional large reactors, SMRs possess a lower capacity of 300 MW but have some important benefits. Their modular construction method decreases the cost of construction, delays, and risks associated with large nuclear projects in the past. SMRs also intend to take advantage of economies of scale in mass production, making them deployable faster and more economically. The compact design of SMRs makes them adaptable for both grid and off-grid applications. SMRs have applications not only in power production but also in district heating and desalination. SMRs can also support other intermittent power sources such as solar and wind energy by providing a stable power supply during periods of intermittency.

E. Integration of SMRs within a Low-Carbon Energy System

Renewable energy sources, such as wind and solar energy, are faced with the challenge of intermittency, as they are dependent on weather conditions and therefore cannot guarantee a steady supply of power. To ensure the development of a stable low-carbon energy system, it is important to integrate firm and flexible energy sources such as SMRs. SMRs can be used in both baseload and flexible operations, which helps to stabilize the power grid. They can also be used in conjunction with renewable energy sources and energy storage solutions to ensure a steady supply of power. This hybrid energy system improves energy security and helps to meet global sustainability objectives.

III. REVIEW OF THE STATE OF THE ART

Small Modular Reactors (SMRs) have advanced significantly by 2026, with over 80 designs across 18 countries—led by the US, Russia, and China—focusing on modular factory builds for outputs up to 400 MW. Only four commercial units operate: Russia's KLT-40S (floating, 70 MW) and China's HTR-PM (gas-cooled, 210 MW since 2023), while leaders like NuScale VOYGR (77 MW, NRC-approved) eye 2029 deployments. A ~22 GW pipeline signals growth, but high first-of-a-kind costs ($89+/MWh), fuel shortages, and regulatory hurdles slow progress toward 2030s scale-up via learning curves for cost parity with renewables.

A. Literature Review

Current studies on the application of Small Modular Reactors (SMRs) have mainly concentrated on the development of dynamic models for power system stability analysis and the integration of hybrid energy systems. One of the major areas of research is the capability of SMRs to engage in load-following and their ability to integrate with intermittent renewable energy resources. Analysis shows that load-following is most economically viable when conventional SMRs are integrated with co-generation applications, such as water desalinization, district heating, or hydrogen production. Moreover, the paper emphasizes that the integration of SMRs with Direct Air Carbon Capture (DACC) technology can greatly enhance the use of thermal energy, thereby increasing the useable energy from 32% to as high as 85%. In terms of economic viability, researchers strongly argue that a sufficient number of SMRs must be deployed to offset their natural lack of economies of scale. Although there are uncertainties regarding the cost-effectiveness of modular design and operating/decommissioning costs, other studies have shown that advanced modular reactors can, in fact, be as economically viable as conventional large-scale reactors. Apart from the economic uncertainties, the major challenges to the deployment of SMRs lie in the complex licensing, legal, and regulatory frameworks.

B. Technology Review

The technology review conducted a group assessment of 70 SMR designs currently under development for electrical power generation. These concepts are broadly classified into

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conventional Generation III+ technologies, which include Boiling Water Reactors (BWRs),Pressurized Water Reactors (PWRs), and integral PWRs (iPWRs), and next-generation Generation IV technologies, which encompass High-Temperature Gas-Cooled Reactors(HTGRs), Liquid Metal-Cooled Fast Reactors (LMFRs), and Molten Salt Reactors (MSRs).The mean electrical power capacity for all reviewed SMR designs typically falls within the range of 100 MW to 200 MW. Notably, the Generation IV technologies are characterized by significantly higher reactor outlet temperatures and thermal efficiencies compared to the Generation III+ technologies. Despite the large number of concepts, only three designs are currently operational and three are under construction, with the majority still in the earlier conceptual, preliminary, or basic design phases. The review argues that for the industry to realize the crucial learning effects (cost reductions from repeated deployments), a maximum of around 10 SMR designs should reach the final commercial stage to ensure each technology achieves sufficient deployment volume. Finally, the compatibility of light-water SMRs with existing power infrastructure makes colocation or repowering of existing coal and gas-fired power stations a viable strategy, which can result in construction cost reductions of 17% to 34%. The deployment of multiple units at one site can also leverage the economies of multiples, reducing construction costs by up to 30%.

IV. POWER SYSTEM INTEGRATION

SMRs are fundamentally designed to provide a firm, non-intermittent, dispatchable source of power. In terms of Baseload Provision and Redundancy, deploying SMRs in multi-unit clusters (e.g., three or four units) is key to ensuring a high minimum output, even during scheduled maintenance. For Load-Following, most concepts are capable of operating in a dispatch range of 20–100%, with ramping capabilities generally between\pm0.5\%/\min and \pm6\%/\min. Furthermore, SMRs can provide critical System Bearing Services, including steady-state voltage control, fast reactive current injections, and local grid stability services like inertia. A major integration advantage is their compatibility with existing power infrastructure, facilitating the repurposing of retired coal and gas-fired power stations through colocation or repowering, which can reduce construction costs by an estimated 17% to 34%.A primary benefit of Small Modular Reactors (SMRs) is their reduced size and division into smaller, modular units, which naturally leads to increased redundancy and the capability to guarantee a higher minimum power output, even during maintenance periods. The maintenance and refueling of these multi-SMR sites can be strategically staggered to maximize the overall baseload supply provision. For example, a cluster of three SMR modules is capable of providing a minimum power output of 67% and can maintain 100% power output for85% of the time, assuming each module has a 95% availability factor and no more than one SMR is under simultaneous maintenance. Beyond steady baseload, SMRs are also designed to operate in a load-following mode. Conventional light-water reactor SMR concepts have a wide dispatch range, with some designs having a range of 20–100% and others 50–100% or 0–100%. Their in entramping capabilities vary from \pm0.5\%/\min to \pm6\%/\min. While the low estramping capabilities (\pm0.5\%/\min to \pm0.8\%/\min) are insufficient for providing fast frequency reserves (FFR) or frequency containment reserves (FCR), all SMR sin directly deliver FFR through their non-controlled inertial response. However, SMRs with higher ramp rates (\pm5\%/\min and \pm6\%/\min) can contribute to FCR and automatic frequency restoration reserves (aFRR). Although curtailing reactor output for load-following reduces SMR productivity, the low variable operating costs mean there is limited economic value in holding back production; therefore, this flexibility is best utilized as a remunerated service in the balancing power market.

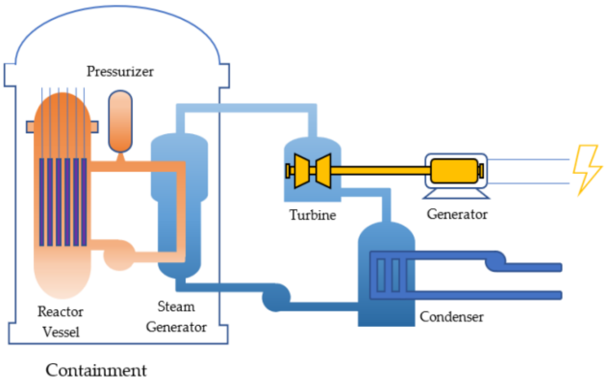

Figure 1. small modular reactor power generation system

A. SMRs Modern Power System

SMRs seamlessly fit into contemporary power grids, combining their hard output with renewables to create stable and low-carbon power networks through multi-unit groups and dynamic operation. They vary their load between 20-100%. ±6%/min for grid support; slow ramps provide inertia/ voltage services, while fast ramps provide paid frequency regulation. Brownfield projects of coal/gas plants reduce expenses by 17-34%. TABLE

Aspect	SMR Perfomance	Grid Benefit	Example Value
Base load	67-100% uptime in 3-unit clusters	Redundancy during maintanance	95% availablability
Load-Following	20-100% dispatch range	Peak/demand responce	Ramps 0.5-6%/min
Grid Services	Voltage control, inertia	Frequency stabilty	FCR/aFRR markets
Site Repowering	Coal/gas plant reuse	Cost saving	17-34% reduction
Hybrid Systems	Solar/Wind/Bess	Seasonal balancing	90%+capacity factor

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V. ENHANCED FLUXIBILITY WITH HEAT STORAGE

A. Technical Perfomance

The integration of thermal energy storage systems is one of the approaches that has been used to improve the operational flexibility of Small Modular Reactors (SMRs). The energy storage system operates by decoupling the constant thermal power output of the reactor from the synchronous turbogenerator's electrical power output, such that the turbine can ramp up or down independently of the reactor core. This new operational mode improves the dispatchability of the SMR, with expected ramp rates increasing substantially to \pm12\%/\min. This is unlike conventional load-following, which does not use thermal energy storage and involves cutting down the reactor power output, hence lowering the productivity of the SMR.

B. Economic Value

The main objective of adding thermal heat storage is to enhance the power market value of the SMR. Although SMRs have low variable operating costs, which inherently limits the economic value of holding back production under simple curtailment, the flexibility added by thermal storage changes this curtailment into an opportunity for revenue. By using the stored heat, this flexibility can be provided as a service into the balancing power market. This guarantees that any power production that might be curtailed from the reactor is compensated by sufficient revenues from the sales of the flexibility service, making the SMR's flexible operation economically valuable. The main objective of adding thermal heat storage is to enhance the power market value of the SMR. Although conventional load-following without storage requires curtailed reactor output, which reduces the productivity of the SMR and offers limited economic value because of the reactor's low variable operating costs, thermal storage changes this operational flexibility into a revenue stream. By using the stored heat, the SMR can provide this flexibility as a service into the balancing power market.

VI. TECHNO-ECONOMIC EVALUATION

SMRs need to offset their natural absence of Economies of Scale—a cost-saving advantage of large-scale facilities—by effectively leveraging other sources of cost savings. This offsetting is accomplished in two ways. The first is through the concept of Economics of Multiples, which describes location-specific cost savings that can be realized by co-locating multiple SMRs at a given site, with cost savings of 10% to 30% expected for two to eight units located together. More significantly, however, is the second method: the Economics of Mass Production.

The central idea here is to take advantage of modularized, prefabricated designs and advanced manufacturing processes (such as series production) to realize cost savings through economies of scale and volume. Moreover, Learning Effects that can be realized from the high-volume, repeated successful deployment of designs are also expected to contribute to cost savings.

A. Economics of Scale

The basic problem for SMRs, as compared to conventional, large-scale nuclear power plants, is that they lack economies of scale. Economies of scale usually imply that the cost per unit of electricity will decrease as the size and capacity of the reactor increase. In order to be economically viable, SMRs have to overcome this problem. SMRs mitigate the lack of economies of scale by using a two-fold strategy, mainly by exploiting economies of mass production. Additionally, they exploit economies of multiples, which are site-specific cost savings that can be realized by locating multiple SMRs at a single power production site. The site-specific cost savings, or economies of multiples, are realized in addition to the technology-specific cost savings that are realized by exploiting the economies of mass production. Additionally, by locating multiple SMRs at the same site, it is possible to share personnel. This is estimated to reduce Operations and Maintenance (O&M) costs by 33%.

B. Economics of Mass Production

The underlying assumption for the commercial viability of Small Modular Reactors (SMRs) is to apply the economic model from economies of scale to economies of mass production. This approach includes maximizing the cost savings from mass production. Unlike their gigawatt-scale predecessors, SMRs apply their modular and prefabricated approach to reduce construction costs and risks. The concepts apply series production and advanced manufacturing methods, such as local electron-beam welding, which make them more applicable to contemporary supply chains than previous small reactors. Notably, the economic model of mass production applies learning effects, which are described as the cost savings from the growing experience gained from multiple deployments of the same design. Consequently, to maximize this approach, each SMR design needs to be produced in sufficient quantities because a broad variety of competing designs would reduce the learning effects for any single technology

VII. CHALLENGES AND FUTURE WORKS

There are a number of major challenges that currently exist to prevent the widespread commercialization of SMRs. There are still a number of uncertainties regarding the techno-economic competitiveness of SMRs and the cost benefit of modular manufacturing. Regulatory barriers, such as the lengthy licensing and legal procedures, also present a challenge. Finally, in order to fully realize the learning benefits of mass production, there must be market concentration; with 70 concepts reviewed, it is generally agreed that only a few, perhaps around 10, should make it to the final stage of deployment.

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A. Challenges

A major challenge that Small Modular Reactors (SMRs) are facing is the requirement of market concentration to achieve the required cost savings. At present, there are more than 70 different SMR designs being developed worldwide. To fully exploit the economies of scale and the key learning effects (cost savings through experience), it is necessary to concentrate the market. It is proposed that only a few designs, perhaps no more than ~10, should finally reach the final commercial implementation stage to ensure that each successful technology reaches the required high volumes for mass production economies and subsequently cost competitiveness.

The successful commercialization of Small Modular Reactors (SMRs) is hindered by several major challenges that must be overcome to realize their full potential in the energy transition. Firstly, there are still major techno-economic uncertainties regarding their overall cost competitiveness; the industry must prove that the expected savings from modularization and mass production truly outweigh the inherent lack of traditional economies of scale. These cost ambiguities range from initial capital expenditure costs to long-term operational and decommissioning costs, which are not yet fully quantified. Secondly, regulatory barriers pose a major challenge, as the current licensing and legal frameworks were mainly developed for large, custom-built nuclear power plants, requiring their adaptation to efficiently address the distinct, standardized, and mass-produced nature of SMR designs. Finally, and crucially, the market requires concentration to realize the necessary cost savings; with over 70 different SMR designs currently under development worldwide, the market is extremely fragmented. To fully exploit the cost savings of mass production and the essential learning effects (cost savings from accumulated experience), it is submitted that no more than about 10 designs should ultimately make it to the final stage of commercialization to ensure that each successful technology reaches the high deployment volumes necessary

B. Future Work

Future research and development efforts must be focused on maximizing the overall system value of Small Modular Reactors (SMRs) within an electricity grid increasingly dominated by intermittent renewable energy sources. A key area of focus involves the continued advancement of co-generation and hybrid systems integration, which requires deeper work into coupling SMRs with non-electric applications such as Direct Air Carbon Capture (DACC), hydrogen production, or industrial and district heating. The aim here is to ensure the thermal energy produced by the reactor is fully utilized, thereby significantly improving the overall economic viability of the SMR. Additionally, future research and development efforts must address the need for peaker-plant optimization; this involves optimizing turbogenerator designs to better handle the flexible, load-following, and potential peaker-plant operational modes that SMRs will be required to perform, ensuring they can efficiently and reliably ramp output quickly to meet the fluctuating demands of the future power system .Future research and development efforts must be strategically focused on maximizing the overall system value of Small Modular Reactors (SMRs) within an electricity grid increasingly dominated by intermittent renewable energy sources. A key area of focus involves the continued advancement of co-generation and hybrid systems integration, which requires deeper work.

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