Decentralized Clean Energy for Rural India: The Role of Small Modular Reactors

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Abstract: India's rapid development and expanding population have intensified the need for sustainable energy solutions. This is particularly significant in addressing the growing disparity in energy access between urban and rural communities. As the country shifts from traditional fossil-fuel-based power generation to cleaner technologies, nuclear energy is poised to play an increasingly vital role. Small Modular Reactors (SMRs) represent a promising option to meet these energy demands in a decentralized and environmentally friendly manner, especially in rural regions. In this perspective article, we explore the technological, economic, social, and environmental advantages of deploying SMRs in rural India. SMRs offer the potential for faster and cheaper build, as well as stable and reliable power, which is essential for driving economic growth in underdeveloped areas. However, several challenges need to be addressed, including regulatory and legislative hurdles that could impede the integration of SMRs into the existing energy mix. This article also suggests solutions such as leveraging India's existing reactor technology expertise, utilizing the mature supply chain framework, co-locating SMRs with renewable energy sources, and advocating for necessary regulatory and legislative reforms. These would help SMRs serve as a crucial bridge in facilitating a smoother transition from fossil fuel plants to clean energy technologies, particularly in underserved rural communities.

Keywords: Small modular reactor, nuclear energy, India, rural, electrification, decentralisation

1. Introduction: India's rapid economic rise and growing population are driving an urgent demand for sustainable and reliable energy solutions. This requires a delicate balancing of energy security and a reduction in the national carbon footprint [1], which is further complicated by the growing divide in energy access between urban and rural areas [2].

Coal-based power generation has been a reliable energy source but is a major contributor to pollution and greenhouse gas emissions [3]. Its centralized nature, heavily dependent on inefficient transmission and distribution networks [4], also leads to inequitable energy access between urban and rural areas [5]. The need of the hour are innovative, clean, and green technologies that can revolutionize energy generation and distribution. Here, nuclear energy has a crucial role to play.

In the transition from fossil fuels to cleaner energy sources, nuclear energy is a vital resource due to its high energy density, low emissions, and consistent power supply. From 1954 till date, India has developed and operated a robust and mature nuclear energy programme which contributes roughly 1.8% to installed national power capacity and nearly 3% to total electricity produced in the country [6]. With 20 operational nuclear power plants, several more under construction and in various stages of development [7], India is committed to significantly expanding its nuclear energy sector.

But the current and proposed fleets of nuclear power plants in India are large-scale centralized entities, located remotely. Which

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means that they are susceptible to the same problems of transmission and distribution as their fossil-fuel counterparts. Also, such large power projects are not cheap and demand a significant capital investment. This is not a problem specific to India. Around the world, nuclear power plants have been shown to be quite expensive investments [8].

However, recent advancements in nuclear technology have opened new possibilities for more flexible and decentralized power generation. As a solution to the capital cost and centralization problem of nuclear power plants, Small Modular Reactors (SMRs) are garnering great attention. SMRs are not a new concept [9], but interest in these advanced nuclear reactor technologies has risen in recent history, especially following certain geopolitical events and a drive to quickly and cheaply provide stable, clean power to communities in the interest of meeting climate goals.

SMRs represent a significant advancement over traditional large nuclear reactors in terms of size, safety, and flexibility. They are smaller, safer, and more adaptable, making them ideal for deployment in remote areas and enabling scalable growth as demand increases. With these advantages in mind, the Indian Government recently proposed its interest in pursuing SMRs [10].

In this perspective article, we discuss the multifaceted advantages of deploying SMRs, specifically in rural India, focusing on their technological, economic, social, and environmental benefits. The insights and information presented here will be valuable for technocrats seeking to understand the broader applications and implications of SMRs, as well as for private companies considering investment opportunities in SMRs within India.

2. A brief glance at SMR technologies around the world: SMRs are compact nuclear reactors that range in size from under 10 MWe to 300 MWe [11], capable of producing 7.2 million kWh of electricity per day [12]. In contrast, large nuclear power plants generate over 1,000 MWe, producing 24 million kWh daily. SMRs can utilize various coolants, such as light water, liquid metal, or molten salt, depending on the technology. While "SMR" is the general term, those using non-light water technology are often referred to as advanced modular reactors (AMRs) and **Error! Reference source not found.** illustrates the distribution of prevailing SMR/AMR design types based on the coolant of choice. Generally, all SMRs generate heat through nuclear fission, which can be used directly or for electricity generation.

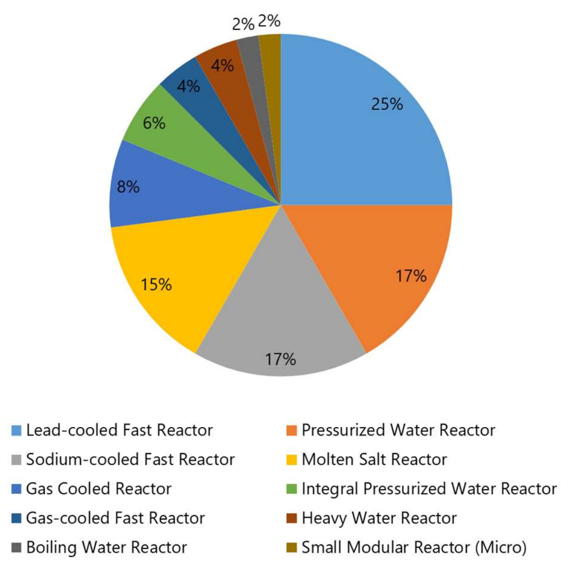

Figure 1. Illustrating the popularity of reactor type among SMR designs around the world. Among the current designs, the Lead-cooled Fast Reactor (LFR) is the most popular choice, followed by Pressurized Water Reactor (PWR) and Sodium-cooled Fast Reactor

Among the leaders in SMR designs are USA and Russia, who contribute to the bulk of current SMR designs, followed closely by China and Japan (**Error! Reference source not found.**). But, though there are large number of designs in existence, only a hand-full are under regulatory review and/or have been licensed, with only two designs under construction (see **Table** ***1***) – the High Temperature Gas Cooled Reactor with Pebble Bed Module (HTR-PM) in China and the light water based KLT-40S in Russia [13].

According to the IAEA dashboard [13], the Indian IPHWR-220 is classified as an SMR and is stated as the only SMR in operation. This represents an effort by the Indian reactor community to modify the mature 220 MWe pressurized heavy water reactor (PHWR) design to enable modularity, factory-fabrication and fast construction times. In line with these efforts, the Indian Government recently put financial thrust into bringing these designs to fruition [14]. By terming these modified 220 MWe PHWRs as 'Bharat Small Reactors (BSR)', the Indian Government is looking to leverage the modification of an already mature and indigenous reactor technology [15] to bring in new private investors to kickstart the SMR run in the country.

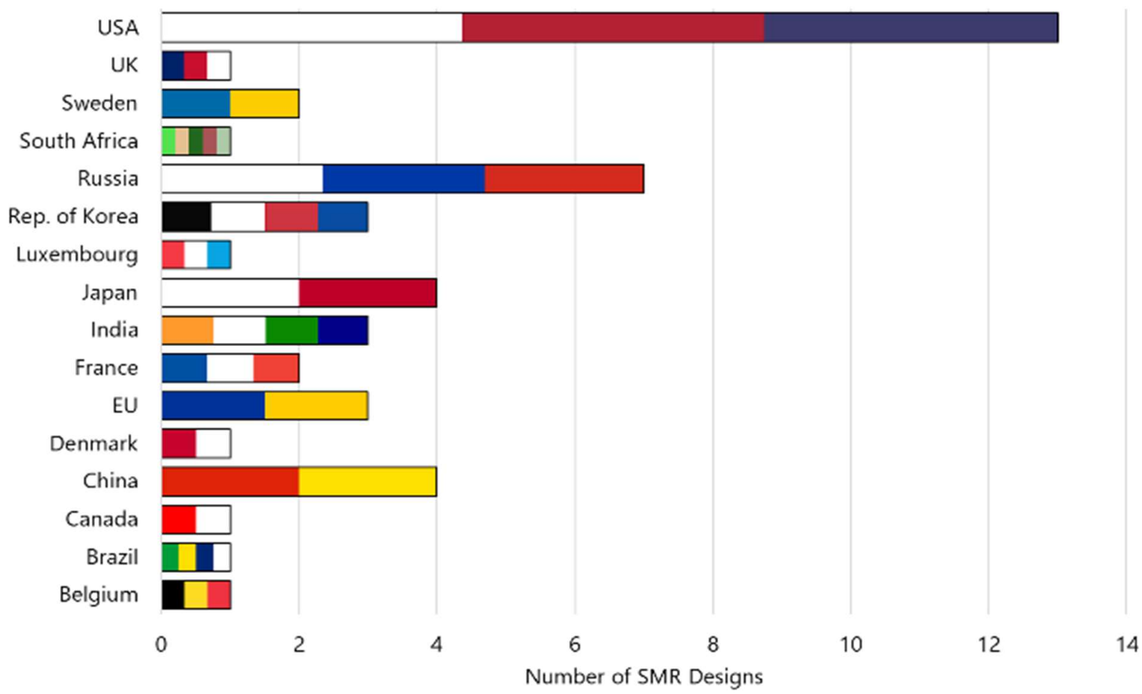

Table 1: Design status of various SMR types [13](refer Error! Reference source not found. **for expansion of acronyms)**

	BWR	GCR	GFR	HWR	iPWR	LFR	MSR	PWR	SFR	SMR micro
Conceptual Design	1	1	1			6	3	2	2	1
Construction		1						1		
Detailed Design							1	1	1	
In Operation				1						
Licensed					1					
On Hold		1								
Under Design		1	1	1	1	6	3	4	5	
Under Regulatory Review					1					

Figure 2. Countries with the largest number of SMR designs [13]

3. Innovative Features of SMRs: It is important to understand what makes SMRs unique and more importantly, useful in the present global scenario of climate change.

The uniqueness of SMRs lies in their compact size and faster construction. Their small power capacity allows for easier integration into smaller grids, better compatibility with renewable energy sources, and more flexible power management. Additionally, the reduced size means less contained radioactivity, leading to lower radiological risks in the event of an accident. Unlike traditional reactors, SMRs are often designed with an integral configuration, which means that various components are incorporated within a single, compact unit. This approach results in a lightweight and transportable reactor, significantly reducing the size of the nuclear island—the core area where the reactor and associated equipment are housed.

In some SMR designs, the primary coolant pumps, which are usually required to circulate the coolant through the reactor, are eliminated. For example, in the integral PWR design, primary circuit components are placed within the reactor pressure vessel, eliminating the need for primary circuit pipework [16]. Instead, these reactors rely on natural circulation of the coolant, driven by gravity and thermal gradients [16, 17]. This reduction in mechanical complexity not only simplifies the reactor design but also frees up space for other critical equipment. In other designs, pumps are mounted either horizontally or vertically on the reactor vessel [18], or even internally at the bottom of the vessel, further enhancing the compactness. Additionally, the use of once-through helical coil steam generators, which have a large heat transfer area within a compact geometry, contributes to the overall efficiency and space-saving design [19]. This simplification makes SMRs easier to operate and less prone to operational disturbances, which enhances their overall reliability and safety.

Safety is a paramount concern in nuclear reactor design, and SMRs have several innovations in this area. One of the key safety features of SMRs is the use of passive safety systems. These systems operate based on natural laws, such as gravity and natural circulation, rather than relying on external power sources or active mechanical components [20]. For instance, in the event of an accident, passive systems can remove decay heat, provide emergency core cooling, and manage containment heat without the need for external intervention [21]. This reduces the likelihood of core damage, thereby significantly enhancing the safety of the reactor. Moreover, some SMR designs incorporate in-vessel control rod drive mechanisms [22], which prevent accidents such as rod ejection—a scenario that could otherwise lead to severe safety issues. Additionally, by eliminating the potential for large and medium breaks in critical reactor components like hot/cold legs, pressurizer surge lines, and primary pump suction/discharge lines [21], SMRs further minimize the risk of catastrophic failures.

The reliability of SMRs is another area where they excel [23]. The simplified and robust design of these reactors inherently contributes to their reliability. By minimizing the number of active components required for operation and maintenance, SMRs reduce the likelihood of mechanical failures. This is complemented using advanced instrumentation and control systems, which feature extensive automation to ensure smooth and consistent reactor operation. Furthermore, the incorporation of advanced diagnostic and prognostic methods allows for early detection of potential issues, enhancing the overall reliability of the system. Highly skilled and trained operators are also a key factor in maintaining the high reliability of SMRs.

Finally, SMRs are poised to be economically competitive, particularly in markets that differ from those traditionally served by large-scale nuclear power plants [24]. They offer an attractive option for developing countries with smaller electrical grids and limited financial resources. The economic advantages of SMRs are a function of several factors, including the economy of mass production of prefabricated modules, a simplified and standardized design, and shorter construction times. Additionally, SMRs have lower operation and maintenance costs, and their modular nature allows for incremental capacity increases. These reactors can also be used for cogeneration and non-electric applications, further enhancing their economic appeal.

4. Socio-Economic Impact of Deploying SMRs in Rural India: Based on the several advantageous features of SMRs, we discuss one specific area of application that would have significant impact – electrification of rural India (see **Error! Reference source not found.**).

One of the most direct economic impacts of deploying SMRs in rural India would be improved energy access. Many rural areas in India still suffer from unreliable or non-existent electricity supply [25], which hampers economic development. SMRs, with their modular and scalable nature, can be deployed in remote and off-grid locations, providing a consistent and reliable power source. This would not only light up homes but also enable the operation of schools, hospitals, and small industries, enabling economic growth and improving the quality of life.

Since SMRs can be deployed closer to the point of consumption, they reduce the need for extensive transmission infrastructure, which is often costly and inefficient. In rural areas, where the distance between energy generation sources and consumers can be vast, transmission losses are a significant issue [26]. By generating power locally with SMRs, these losses can be minimized, making electricity more affordable and reliable for rural populations. This decentralized approach also makes the energy system more resilient to disruptions.

Agriculture being the backbone of rural India's economy, often suffers from unreliable electricity supply, affecting irrigation, storage, and processing of agricultural products. And over the years, demand for electricity by the agricultural sector has only risen [27]. SMRs could

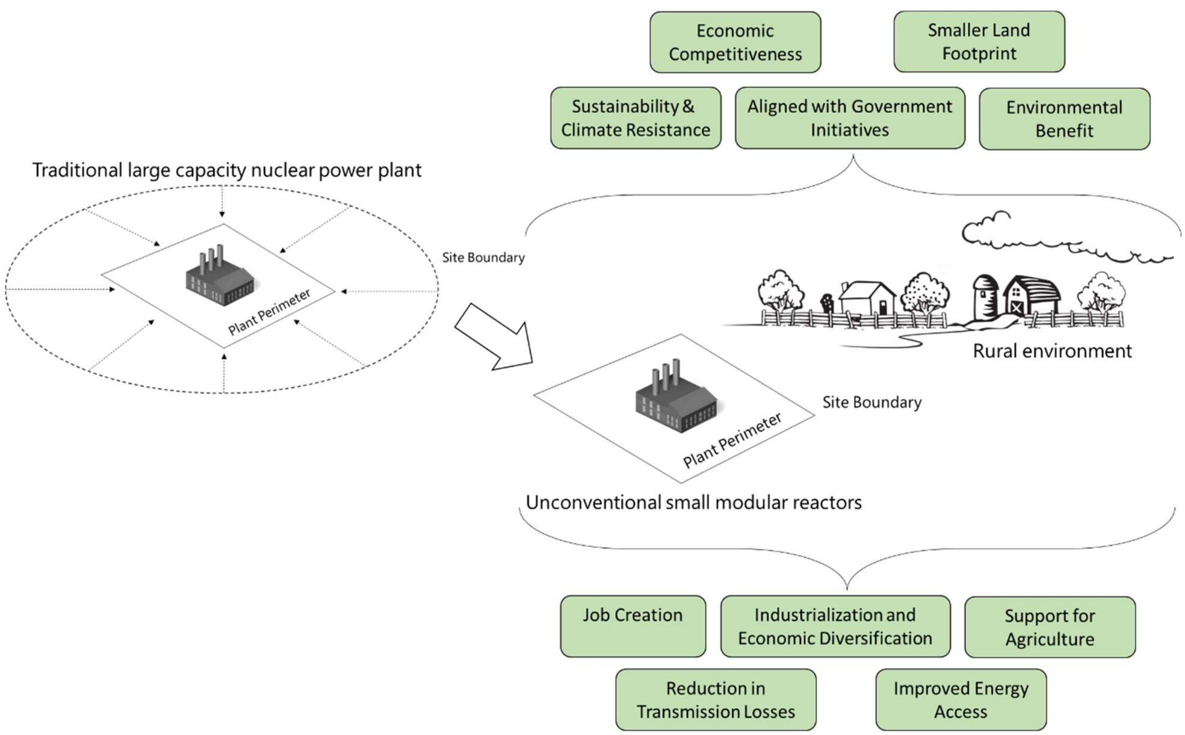

Figure 3. Illustrating the several benefits of deploying small modular reactors (SMRs) in rural environments

provide a stable and continuous power supply, enabling the use of electric pumps for irrigation, cold storage facilities for perishable products, and processing units. This would increase agricultural productivity, reduce post-harvest losses, and enhance the incomes of farmers.

The availability of reliable and affordable electricity is also crucial for industrialization. SMRs can support the establishment of micro, small and medium-sized enterprises (MSMEs) in rural areas, which in turn can create jobs, promote entrepreneurship, and stimulate local economies. Industries such as agro-processing and textile manufacturing could thrive with access to consistent power. The growth of these industries would lead to a more diversified rural economy, reducing dependency on agriculture and creating new avenues for income generation.

The deployment of SMRs could stimulate local economies through job creation. The construction, operation, and maintenance of SMR facilities would require a skilled workforce [28], leading to the creation of new jobs in rural areas. Additionally, the need for supporting infrastructure, such as roads, communication networks, and housing for workers, would further boost local economies. The presence of a stable power supply could also attract businesses and industries to rural areas, further enhancing economic opportunities.

The economic competitiveness of SMRs lies in their modular construction, which allows for economies of scale and shorter construction times compared to traditional large reactors [24]. This means that the initial capital investment required for SMRs can be lower, making them a financially viable option for rural electrification. Additionally, the lower operation and maintenance costs of SMRs, coupled with their ability to be mass-produced, could result in cost savings that could be passed on to consumers in the form of lower electricity tariffs. This would make electricity more affordable for rural populations, increasing their disposable income and enabling further economic activity.

The deployment of SMRs also allows for alignment with several government initiatives aimed at promoting rural development and sustainability. For example, SMRs could support the Indian government’s goals under the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya) scheme [29], which aims to provide universal household electrification. Additionally, SMRs could contribute to the Smart Cities Mission [30] by powering smart rural hubs that integrate energy, water, and waste management systems. By supporting these initiatives, SMRs could attract government funding and policy support, further enhancing their economic impact in rural India.

5. Environmental Considerations and Benefits for Rural India: One of the most significant environmental benefits of SMRs is their ability to generate electricity with minimal greenhouse gas (GHG) emissions. Unlike fossil fuel-based power plants, which are major contributors to climate change, SMRs produce energy through nuclear fission, which does not emit carbon dioxide during operation. For rural India, many communities rely on biomass or diesel generators for energy. Air pollution is often exacerbated by the burning of biomass for cooking and heating [31], as well as by diesel-powered irrigation pumps and generators [32]. SMRs can provide a reliable and clean source of electricity that reduces the need for these polluting practices. Access to clean electricity could lead to a shift from biomass to electric stoves and heaters, which would improve indoor air quality and reduce respiratory diseases that are common in rural areas [33]. Furthermore, the availability of electricity from SMRs could power electric vehicles and machinery, further cutting down on local air pollutants.

Traditional large-scale power plants require vast amounts of water for cooling, which can strain local water resources, especially in rural areas where water is already scarce. SMRs are designed to be more efficient in their use of water [34], and some designs even utilize air-cooling systems that further reduce water usage. By deploying SMRs in rural areas, the pressure on local water resources can be alleviated, preserving these resources for agricultural use and daily consumption.

SMRs also have a much smaller physical footprint compared to traditional nuclear power plants [11] (see **Error! Reference source not found.**), making them suitable for deployment in rural areas with limited available land. Their compact size means they can be sited in locations that minimize disruption to local ecosystems and agricultural land. This is particularly important in rural India, where land is a critical resource for farming and biodiversity. The smaller land requirement of SMRs ensures that valuable agricultural land is preserved, and local ecosystems remain intact. Additionally, since SMRs can be deployed as decentralized power sources, they reduce the need for extensive transmission networks and minimize the environmental impact associated with energy infrastructure development.

Overall, by providing access to reliable and clean electricity, SMRs can promote more sustainable agricultural practices in rural India. For example, SMRs can power energy-efficient irrigation systems, reducing the environmental impact of water extraction from rivers and groundwater sources. Additionally, electricity from SMRs can support the development of cold storage facilities, which reduce food wastage and enhance the sustainability of the agricultural supply chain. By enabling these practices, SMRs contribute to more sustainable rural economies and reduce the environmental footprint of agriculture.

The deployment of SMRs can also contribute to climate resilience in these areas by providing a stable and reliable source of electricity that is not dependent on weather conditions. Rural areas in India are often more vulnerable to the impacts of climate change,

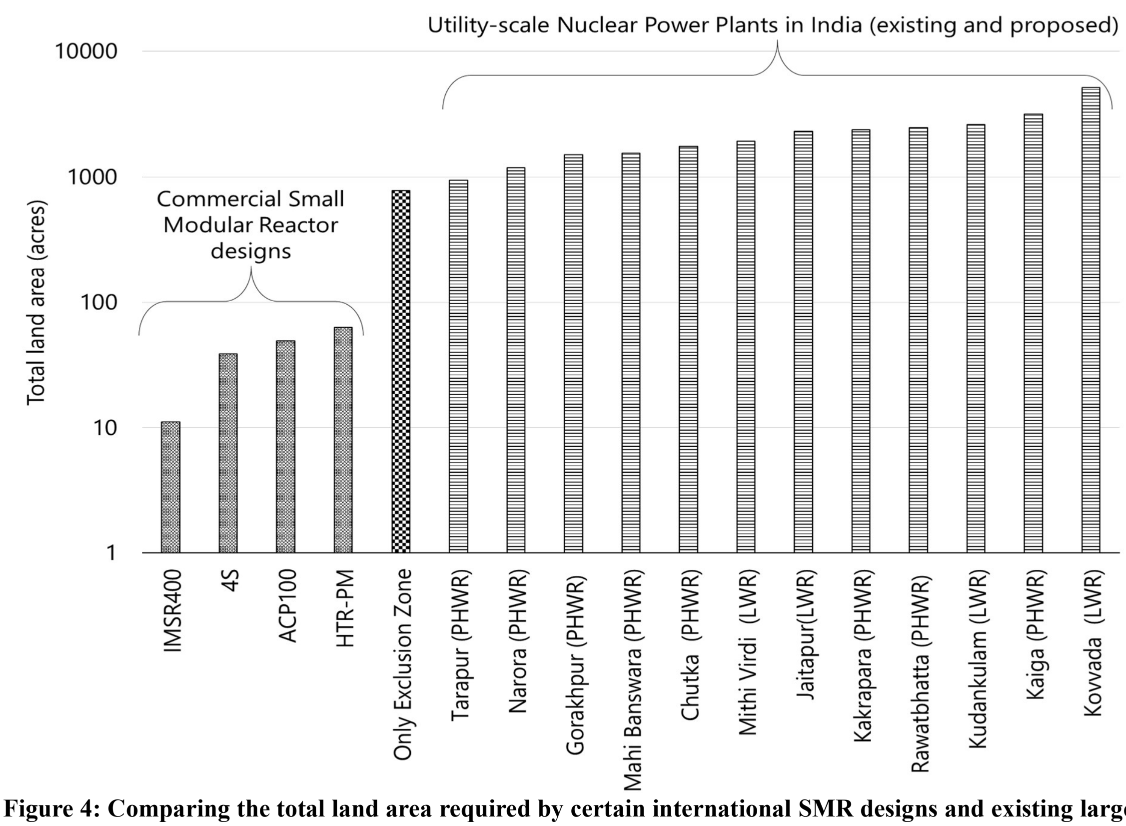

Figure 4: Comparing the total land area required by certain international SMR designs and existing large capacity nuclear power plants in India

such as extreme weather events, droughts, and changing rainfall patterns. Consistent power supply from SMRs can help rural communities better adapt to climate variability, ensuring that essential services, such as water supply and communication, remain operational during extreme events. By enhancing climate resilience, SMRs support the long-term sustainability of rural communities.

6. Challenges in Deploying SMRs: While SMRs exhibit several benefits for rural India, their development and deployment pose certain institutional, economic and regulatory challenges.ndia's nuclear regulatory framework is primarily designed for large-scale nuclear reactors. Adapting this framework to accommodate the unique characteristics of SMRs is a significant challenge. SMRs often have different safety profiles, operational modes, and deployment scenarios compared to traditional reactors, which may require a new set of regulations or the modification of existing ones [35]. The process of developing, approving, and implementing these regulations can be time-consuming, potentially delaying SMR projects [36]. Additionally, the decentralized and modular nature of SMRs, which may be deployed in multiple small units, could complicate the regulatory process, especially in rural areas with limited regulatory oversight.

1) The initial capital investment required for SMR development and deployment can be substantial [24], even though SMRs are generally less expensive than large reactors. Securing financing for these projects in rural India, where the return on investment might be uncertain, poses a significant challenge. Investors may be hesitant due to the perceived risks associated with nuclear energy, regulatory uncertainties, and the long payback periods typical of nuclear projects [37]. Furthermore, the economic viability of SMRs in rural areas depends on factors such as local electricity demand, the availability of skilled labour, and infrastructure costs. In regions with limited industrial activity and low population density, generating sufficient revenue to justify the investment in SMRs can be challenging.

2) Deploying SMRs in rural India requires significant infrastructure development. This includes transportation networks capable of handling the heavy and complex components of SMRs, as well as the construction of facilities for assembly, operation, and maintenance. In many rural areas, existing infrastructure may be inadequate, necessitating substantial investments in roads, bridges, and other logistics systems. Additionally, SMRs require reliable grid connections to distribute the electricity they generate. In remote regions, where grid infrastructure may be underdeveloped or non-existent, creating the necessary connections could be costly and logistically challenging.

3) Nuclear energy has historically faced public scepticism and opposition, often due to concerns about safety, nuclear waste, and environmental impact [38]. In rural India, where awareness of nuclear technology may be lower, gaining public acceptance for SMRs could be difficult. Local communities might resist the deployment of SMRs due to fears of accidents or radiation exposure, particularly in regions that have limited experience with nuclear facilities. Building trust and ensuring public support will require comprehensive community engagement, education, and transparent communication about the safety and benefits of SMRs.

4) Operating and maintaining SMRs requires a skilled workforce with expertise in nuclear engineering, safety, and operations [28]. However, in rural India, the availability of such skilled professionals may be limited. Training and retaining qualified personnel in remote areas can be challenging, particularly if these regions lack educational and vocational training institutions focused on nuclear technology. The need to develop local expertise could delay SMR projects and increase operational costs, as specialized training programs and recruitment efforts would be necessary to build a capable workforce.

5) The successful deployment of SMRs in rural India depends on the availability of a robust supply chain capable of producing, transporting, and assembling the modular components. However, the nuclear manufacturing industry in India is still developing, and there may be gaps in the domestic supply chain that need to be addressed. For example, the production of specific materials, components, or advanced technologies required for SMRs might be limited or non-existent in India, leading to dependence on imports, which could increase costs and lead to delays. Furthermore, establishing manufacturing facilities in rural areas may be challenging due to logistical constraints and the lack of supporting industries.

6) While SMRs are designed to have a smaller footprint than traditional reactors, deploying them in rural areas still raises environmental and land use challenges. Site selection must consider the potential impact on local ecosystems, water resources, and agricultural land. In rural India, where land is often a critical resource for farming and biodiversity, finding suitable sites that meet safety and environmental requirements without disrupting local communities or natural habitats can be difficult.

7) The integration of SMRs into India's energy market poses its own set of challenges, particularly in rural areas where energy demand may be inconsistent or growing slowly. SMRs are designed to be economically competitive, but their success depends on stable and predictable demand for electricity. In rural areas with lower energy consumption or seasonal variations in demand, ensuring consistent utilization of SMRs can be challenging. Moreover, the pricing of electricity generated by SMRs needs to be competitive with other sources of energy, including renewables like solar, which is becoming increasingly cost-effective in India [39]. Balancing the cost-effectiveness of SMRs with the need to provide affordable energy to rural communities is a complex challenge.

8) With SMRs, long-term sustainability and the management of nuclear waste remain critical concerns. Rural areas may lack the infrastructure required for the safe handling, storage, and disposal of nuclear waste, which could become a significant issue over time. Ensuring that the waste produced by SMRs is managed in an environmentally sound and socially acceptable manner is crucial, particularly in regions where there may be limited regulatory oversight or public understanding of nuclear waste issues. Developing a comprehensive waste management strategy that addresses the specific needs of rural areas is essential for the long-term success of SMRs.

7. Strategic Solutions and Recommendations: As a way around these challenges, we offer some technological, economic, regulatory, environmental, social and policy-level solutions.

Technological

1) Promote the use of standardized designs for SMRs, which can streamline manufacturing and reduce costs.
2) Invest in the development of a robust domestic supply chain for SMR components. Encourage local manufacturing of key components through subsidies, tax breaks, or preferential procurement policies. This can reduce dependence on imports and ensure timely delivery of essential parts.
3) Implement pilot SMR projects, especially by private vendors, in selected rural areas to demonstrate their safety, reliability, and economic viability. Successful pilot projects can serve as benchmarks, helping to refine regulations and build confidence among stakeholders.
4) Develop hybrid energy systems that combine SMRs with renewable energy sources like solar, wind, and biomass. This can optimize energy production and provide a stable power supply,

particularly during periods of low renewable energy generation. It also enhances reliability and resilience while reducing transmission losses.

5) Implement advanced grid management technologies to integrate SMRs with rural microgrids, ensuring stability and efficient load management.

Economic

6) Explore innovative financing models, such as crowd-funded investment, green bonds, or international funding from climate and energy transition funds, to support SMR deployment in rural areas.
7) The government can offer guarantees to mitigate financial risks for first-time investors, particularly in rural projects where returns may be uncertain. This can include power purchase agreements (PPAs) with assured offtake by state utilities or local governments.
8) Encourage public-private partnerships to share the financial burden of SMR projects. The government can provide subsidies, tax incentives, or low-interest loans to attract private investment in SMRs, particularly for rural electrification.

Regulatory

9) The Indian nuclear regulatory body, the Atomic Energy Regulatory Board (AERB), could develop a specialized regulatory framework for SMRs. This framework should account for the unique safety features, modular construction, and deployment scenarios of SMRs.

Environmental

10) Conduct thorough environmental impact assessments (EIAs) and land use studies to identify optimal sites for SMR deployment in rural areas.

Social

11) Launch public education campaigns in rural areas to raise awareness about the benefits and safety of nuclear energy, specifically SMRs. These campaigns should address common concerns and misconceptions, using simple language and relatable examples to build trust and acceptance.
12) Establish vocational training centres in rural areas to develop a local workforce skilled in nuclear technology or its supply chain, specifically tailored to the needs of SMRs.
13) Provide incentives for skilled professionals to work in rural areas, such as housing allowances, educational benefits for their children, or career advancement opportunities. This can help attract and retain the necessary talent for operating and maintaining SMRs in remote locations.
14) Establish community benefit programs that provide direct advantages to rural communities hosting SMRs. This could include revenue-sharing schemes, infrastructure improvements, or community development projects funded by SMR operators.

Policy

15) The Indian government should provide clear and consistent policy direction supporting SMR deployment, particularly in rural areas. This includes setting targets for rural electrification using SMRs, offering incentives, and ensuring alignment with broader energy and climate policies.
16) Maintain transparency in communicating the safety measures, environmental impact, and long-term benefits of SMRs to the local population. Open communication channels between project developers, regulators, and communities can help build trust.
17) Develop comprehensive infrastructure plans that integrate SMR deployment with other rural development

initiatives. This can include the simultaneous development of roads, grid connections, and water supply systems, reducing overall costs and ensuring that SMRs are part of a broader rural development strategy.

8. Conclusion: In conclusion, the deployment of SMRs in rural India offers a promising solution to the country's growing energy demands, particularly as it seeks to bridge the gap between urban and rural energy access. SMRs provide an opportunity for sustainable, reliable, and decentralized power generation that can significantly boost rural economies by supporting agriculture, industrialization, and overall quality of life. Though the path to widespread SMR adoption is fraught with challenges, including adapting India's regulatory framework, securing financing, developing infrastructure, and gaining public acceptance, these challenges can be addressed by a multi-faceted approach. India's existing nuclear expertise needs to be leveraged, public-private partnerships need to be fostered, and SMR deployment must align with national energy and climate goals. By implementing targeted technological, economic, and policy-driven strategies, India can overcome the above barriers and unlock the full potential of SMRs for rural electrification.

Conflict of Interest: Authors declare no conflict of interest.

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