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Measuring progress in a new energy technology deployment: The case of small modular reactors

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ABSTRACT

Small modular reactors (SMRs) are increasingly recognised as a promising solution to address the global energy trilemma of security, affordability, and sustainability. However, despite their potential, SMRs face systemic challenges that hinder their progression from conceptual designs to full commercial deployment. While existing literature identifies critical barriers individually, such as policy, regulation, financing, and supply chain development, integrated frameworks for assessing systemic progress remain scarce. This study addresses this gap by developing a novel, structured framework for evaluating the readiness of SMR deployment. Drawing on document analysis and 25 semi-structured expert interviews, a thematic analysis guided by abductive reasoning was conducted to identify the critical threshold criteria for the deployment of SMRs. A framework was then developed and operationalised across five core areas: policy support, licensing and regulatory readiness, financial viability, supply chain availability, and commercial readiness. The resulting framework offers policymakers, investors, and developers a practical tool for identifying bottlenecks, measuring systemic progress, and accelerating SMR deployment.

1. Introduction

As global energy demand continues to rise, there is an immense strain on the ability to produce sufficient energy (security) at a reasonable price (affordability) without harming the environment (sustainability) (Liu et al., 2022; Zhao et al., 2024). The balancing act between the aspects of security, affordability and sustainability is commonly referred to as the energy “trilemma” in the energy industry (World Energy Council, 2024). This balance is essential for promoting economic growth (Khan et al., 2022; Yu et al., 2023).

Governments and policymakers are exploring numerous strategies to address this situation. Existing energy technologies, such as renewables, natural gas, and traditional nuclear power, are increasingly being deployed to meet these needs (Gunningham, 2013). Concurrently, emerging technologies are being developed to provide innovative solutions and further address the complexities of the energy trilemma (Helm, 2014; Mathew, 2022). However, these next-generation energy technologies face several challenges in transitioning from low technology readiness levels to commercialised products.

The small modular reactor (SMR), a newer generation of nuclear power technology, is a prime example of an emerging innovation in the energy sector. SMRs are designed to deliver significant power output relative to their compact footprint, often generating up to 300 MW (MW) per unit, making them a highly efficient solution for energy generation. Their modular design allows for the manufacturing of components and systems in a factory-controlled environment and transportation to the site for assembly (IAEA, 2021b). This process reduces construction risks, ensures higher quality control, and can expedite deployment timelines (Ingersoll, 2009; Hidayatullah et al., 2015).

SMRs do not benefit from economies of scale as large reactors (LR) do (Locatelli et al., 2014). Instead, they rely on the “economies of multiples”, which means that achieving the same power output as an LR requires deploying more SMRs. This approach enables SMRs to leverage mass production, where replicating standardised designs can reduce costs through learning effects and strengthen the supply chain (Carelli et al., 2010; Locatelli, 2018).

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Despite their advanced technology and associated benefits, SMRs face significant challenges in their deployment. Many potentially available SMR designs lack clients and investments (Ramana, 2021). The existing literature highlights various areas contributing to this situation. For example, Nian et al. (2022) highlight the policy mechanisms needed to support the creation of an optimal market for SMRs. Sam et al. (2023) discuss the complex regulatory and licensing challenges and barriers that deter potential investments. Financing and economic viability of SMRs remain major hurdles, given the substantial funding required to validate technology innovations, establish the manufacturing and assembly facilities and construct the reactors (Mignacca and Locatelli, 2020; Mignacca et al., 2020). The economic competitiveness of SMRs compared to other energy technologies is essential for attracting investments (Shropshire, 2011; Asuega et al., 2023). Additionally, the supply chain considerations for integrating modular designs and scaling up present further challenges (Wrigley et al., 2021; Lloyd et al., 2021; Ahmad and Usman, 2025).

Countries with significant government involvement and funding support, such as China and Russia, have managed to build their first-of-a-kind (FOAK) SMR units and obtain the license to operate (NEA OECD, 2024). Two such cases are the Akademik Lomonosov, a 35 MW KLT-40S floating SMR in Russia, and a 210 MW high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration plant in China. Nonetheless, the transition of these FOAK units to serial deployment remains limited (Ramana, 2021). In Russia, although the Akademik Lomonosov is operational, no further units have been ordered. The state has shifted focus toward the RITM-200 design, an evolution of the KLT-40S (NEA OECD, 2025). In China, by contrast, there has not yet been a confirmed follow-up order for additional HTR-PM units, although other SMR designs such as the ACP100 are progressing through licensing and early construction phases (NEA OECD, 2025).

Conversely, other countries pursuing SMRs with a mix of government and private investment are falling behind. For instance, while NuScale Power became the first SMR reactor to obtain design certification in the United States, its project with Utah Associated Municipal Power Systems (UAMPS) was abandoned due to escalating costs (NuScale, 2023). In the United Kingdom, Rolls-Royce SMR has secured sufficient funding for the detailed design and licensing stages (Rolls-Royce, 2021) and has been selected as the government's preferred SMR design (Department for Energy Security & Net Zero, 2025). However, as of mid-2025, the developer has not yet secured sites for deployment, and project timelines remain uncertain. On the other hand, the GE-Hitachi BWRX-300 SMR vendor in Canada has made encouraging progress in the licensing review and has secured investments for its project in Darlington (GE Vernova, 2023). It is now building its supply chain (World Nuclear News, 2024).

These examples are not exhaustive but highlight the complexity of measuring progress in SMR deployment. Given the diversity of individual projects, each at different stages of development and facing unique challenges, it is difficult to measure the overall progress towards achieving a fully commercialised SMR programme. Progress in one area can stagnate if others lag, potentially causing the project to fail despite isolated successes.

While existing literature effectively identifies individual areas affecting SMR commercialisation, frameworks that combine them into a single systemic and structured tool remain scarce. This gap limits the ability of stakeholders to fully understand and strategically address the interconnected challenges SMR technologies face. To address this challenge, this study sets out to achieve two research objectives (RO): (1) to identify the critical systemic areas influencing SMR deployment and (2) to develop a novel framework for measuring progress towards commercialisation. The study examines the key systemic areas and integrates them into a structured framework designed to assist stakeholders, including policymakers, investors, and developers, in simultaneously measuring progress across multiple critical areas, identifying bottlenecks, and accelerating SMR deployment.

2. Methodology

2.1. Research design

This study employed qualitative research methods involving document analysis and semi-structured expert interviews. Thematic analysis guided by abductive reasoning (Braun and Clarke, 2006; Timmermans and Tavory, 2012) was used for data analysis. Abductive reasoning is an iterative process that integrates existing theoretical concepts with empirical data to generate the most plausible explanations for the phenomena under study (Timmermans and Tavory, 2012). The research design is broken down into three stages, as summarised in Fig. 1 below.

2.2. Data collection and analysis

In the first phase, the authors conducted a document analysis using secondary data from key nuclear energy institutions, including reports from the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency (NEA), and the World Nuclear Association (WNA). The analysis helped identify and categorise the main discussion areas associated with SMR deployment and formulate relevant interview questions.

Following this, 25 nuclear experts from diverse backgrounds, including financial, technical, legal, and regulatory fields, were interviewed to gather further insights. Table 2 in Appendix A presents the profiles of the interviewees, along with the corresponding interview durations. The interviewees represented different geographic perspectives, including North America (United States, Canada), Europe (United Kingdom, Italy and France), and Asia (China). The initial experts were chosen through purposive sampling based on their expertise, while the subsequent ones were identified through snowball sampling (Palinkas et al., 2015).

In the second phase, the recorded interview conversations were transcribed and coded on NVivo 14. The authors conducted a thematic analysis of the interview transcripts to identify the main areas critical to the deployment of SMRs. Initial open coding was conducted to capture emergent concepts. As more data were collected, axial coding techniques were applied to refine and group related codes into broader second-order themes, which led to the development of aggregate dimensions (Corbin and Strauss, 2008; Gioia et al., 2013). An example of the coding structure developed from the thematic analysis is provided in Table 3 of Appendix B, showing how first-order quotes were abstracted into second-order themes and aggregate dimensions. After approximately 18 interviews, theoretical saturation was reached, and no substantially new codes or themes emerged. The subsequent seven interviews confirmed the stability and robustness of the identified coding framework.

Finally, in the third phase, the authors used the primary and secondary findings to abductively code the threshold criteria and develop a general framework for measuring progress towards commercialising new energy technologies. The authors framed these threshold criteria into a "yes" or "no" question approach to demonstrate objectivity. The "yes" indicates progress in that area, whereas the "no" indicates that the area requires improvement. The criteria were iteratively reviewed, with the authors consistently challenging the questions asked to ensure the robustness and generalisability of the framework.

3. Results

3.1. General framework for measuring progress in SMR

The main findings highlight policy support, licensing and regulatory readiness, financial viability, supply chain availability, and commercial viability as key areas to the systemic deployment of SMR technology. As presented in Table 1, the framework encompasses these five main areas. The interview findings have been refined into practical threshold

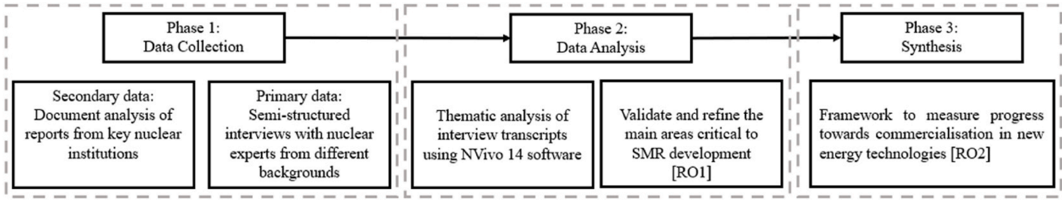

Fig. 1. The research design employed in this study.

criteria, representing specific requirements to advance SMR technology from the conceptual phase to commercialisation. Meeting these criteria indicates progress, while unmet criteria highlight areas requiring further support. The interview code column links to the reference interviews that discuss the concepts associated with the different threshold criteria. In addition, the authors provided examples based on the primary and secondary data to indicate the positive measures of progress. These examples facilitate answering the questions and identifying potential areas for improvement. The authors designed the questions to operationalise the progress made in the overall deployment of SMR technology.

3.2. Main areas critical to the systemic deployment of SMRs

The main findings from the interviews are presented below, along with supporting arguments from the participants. These findings formed the basis for developing a framework to measure progress in SMR deployment.

3.2.1. Policy support

"There's a big difference between the excitement over the technology, its ability to solve some big problems and the reality of putting a shovel in the ground and starting to build one. So that's the gap that we have today" (I11).

Despite the enthusiasm among SMR developers for their conceptual designs, the stark reality is that a fully established commercial market for SMRs has not yet emerged in most regions, particularly in Europe and North America. Most SMR designs remain in the conceptual phase and are not yet tangible products that can be priced and sold to potential buyers. *"The biggest challenge to me is how you get from where you are today to commercial final investment decision"* (I17), observed an expert. These designs require substantial early-stage financing support to progress through detailed engineering, regulatory approval, and development and demonstration of their representative designs.

Investors are hesitant to commit funds until SMR designs validate their technological and operational readiness. While the early-mover advantage can help vendors secure a dominant market position, *"no one wants to be the first to get there while being exposed to financial disaster"* (I08). As one financial expert aptly summarised the situation, *"The challenge here is that SMRs into deployment feels up to 10 years away. This is the problem for investors who are looking for immediate opportunity"* (I17). This creates a paradoxical situation where SMR developers struggle to secure investment without validated designs, yet they need investment to validate these designs. There is an impasse in raising development capital for financing and licensing FOAK SMR designs, which subsequently delays the progress of SMRs towards commercialisation.

The interview responses highlight the crucial role of governments in creating an enabling environment for the FOAK SMRs. As one interviewee emphasised, *"At the outset of developing a nuclear programme, you need to have a governmental framework that authorises the use of the technology, provides basic legislative standards and establishes the regulatory framework"* (I23), and another stressed that *"policy* support *needs to be set, followed by the nuclear law framework"* (I20). This high-level policy support is crucial for overcoming current challenges, particularly given that electricity is a fundamental part of national infrastructure, and *"ultimately failure of the electric system, if the lights are not on, the government bears the policy risk"* (I14). A long-standing commitment to a fleet deployment programme centred around specific designs, along with sufficient financial backing, is necessary to advance these designs past the conceptual stage. This will facilitate the economic deployment of the SMR design and secure a stable market pipeline. Interviewees also highlighted the importance of public support, as it fosters broader acceptance of SMR technologies and helps build the social license needed for their successful deployment.

Furthermore, such supportive policies will incentivise the development of a domestic supply chain and the expansion of the nuclear workforce to enable the scale of deployment. By providing confidence to the nuclear industry and potential investors that *"This is going to be the first of a programme of many plants rather than a one-off with uncertainty about what the future looks like"* (I17), governments can help SMR developers attract additional development capital from private investors. This comprehensive support will enable them to overcome the early-stage financing gap.

3.2.2. Licensing and regulatory readiness

The deployment concept associated with the SMR programme is ahead of its regulatory framework. The differentiator is in the economics, as explained by one of the experts, *"There has to be an understanding that for SMRs to be economical, the economies of numbers have to help overcome the economies of scale, and what that means is there has to be a change in perspective …"* (I18). Achieving economic viability for SMRs requires a shift towards volume factory production, as they need a broader market to reach the required numbers. Relying solely on the domestic market of one specific country is insufficient. The exportation and replication of SMRs across multiple countries are necessary. This can only be achieved if *"the practicality of seeing the replication of SMR technologies"* (I17) exists within multiple regulatory environments. Site-specific changes will always exist because *"the envelope of all possibilities around the world increases the cost of the design"* (I22). Another expert points out, *"you can do the first-of-a-kind with existing regulation; [in order] to have mass production of SMRs, you need a dedicated licensing framework to scale up"* (I19). Furthermore, *"the licensing process should be greatly reduced in terms of risks"* (I01) after deployment of the FOAK and by standardising the designs and their associated systems and components. Frequent redesigns during the licensing process make SMRs economically unfeasible and challenging to finance, as has been the case with LRs.

There is increasing international regulatory collaboration between countries pursuing the same SMR designs. *"… a regulator in one country may build upon the licensing approval from another country by sharing information or accepting parts of what has been done before"* (I18), explained one expert. The interviewees believe that recognising the design certification approved by regulators in another country with a mature regulatory framework and not re-assessing the SMR designs from scratch in the destination country is crucial for enabling the practical replication of SMR designs across different jurisdictions. Such a unified approach will reduce the time and complexity of obtaining approvals, leading to a more efficient and predictable pathway for the global deployment of SMRs.

The regulatory bodies are under immense strain as more SMR vendors seek to enter the licensing process. Governments' backing extends to investing in the nuclear regulators to meet the projected scale of

Table 1
Framework for measuring progress in SMR deployment.

	Identified threshold criteria	Interview Code	Examples to satisfy threshold criteria
Policy support	Is there strong government support for the technology?	I04, I06, I07, I08, I09, I11, I12, I13, I14, I16, I17, I20, I23	The government has issued policies recognising the role of SMRs in its energy mix (NEA OECD, 2021). | The government has committed to deploying a fleet of SMRs (IAEA, 2021a). | The technology selection of viable SMR designs has been made (NEA OECD, 2021).
	Is there sufficient public support for the technology?	I04, I06, I07, I11, I13, I15, I18	There is strong stakeholder engagement to build public confidence in the technology and foster public support and acceptance of the project and its siting (NEA OECD, 2022b; IAEA, 2024b).
	Have significant funding and investments been made in technology research, development, and demonstration programmes?	I02, I03, I06, I09, I10, I12, I14, I15, I16, I17, I18, I24	Grant funding should be provided to support the technology development, licensing, and demonstration projects (IAEA, 2024a). | Development programmes are in place to support advanced manufacturing techniques and enhance the capability and capacity of the existing workforce, including nuclear regulators (IAEA, 2021a; IAEA, 2024b).
Licensing and regulatory readiness	Is there a fit-for-purpose regulatory and licensing framework aligned with the economic deployment of the technology?	I01, I04, I05, I07, I08, I10, I11, I13, I15, I16, I19, I20, I22, I23	Reforms to the existing regulatory and licensing frameworks are being undertaken to facilitate the licensing of SMRs (NEA OECD, 2021). | A timely licensing framework is also being developed to foster market deployment (NEA OECD, 2020).
	Are there measures taken to streamline the regulatory and licensing review of the technology?	I01, I05, I08, I10, I12, I13, I14, I15, I18, I21	National regulators deploying similar technology designs have established a memorandum of cooperation, facilitating their collaboration in the reactor design review and licensing processes (NEA OECD, 2022a).
	Are all the necessary approval processes in place to advance the project through various stages of the licensing application?	I01, I03, I05, I06, I07, I10, I13, I16, I20, I21, I22	The regulatory framework has a pre-licensing process that enables an early engagement between the licensee and regulatory body to understand the regulatory requirements and expectations (IAEA, 2022a). | Necessary measures have been established for regulatory oversight of in-factory manufacturing and testing, factory commissioning, and transportation (World Nuclear Association, 2015; IAEA, 2022a).
Financial viability	Is there a strong and complete ownership team?	I11, I12, I14, I16, I17, I18, I24	The ownership team comprises a site owner and a knowledgeable customer with strong project management capabilities and experience in nuclear construction and operation to oversee the project throughout its lifecycle (IAEA, 2024a). | The project developer has strategic partners and investors with strong balance sheets and risk appetite (NEA OECD, 2020).
	Is there an experienced and capable project delivery team?	I11, I12, I14, I16, I17, I18, I24	The project delivery team has significant experience in delivering NPP projects and has the capacity and capability to deliver the project within the proposed schedule (IAEA, 2024a).
	Are there assurances of a secure project revenue stream to the owner/operator of the plant?	I04, I08, I09, I12, I13, I14, I16, I17	There is a structure for a cost-recovery mechanism in place, leveraging the reliability and stability of the revenue stream generated by the project (IAEA, 2024a). | There is a stable, long-term, creditworthy offtake arrangement for power purchase, such as contracts for difference (CfD) or regulated asset base (RAB) model (IAEA, 2024a).
	Is there adequate government and/or private support to finance the project?	I04, I07, I08, I09, I11, I12, I13, I14, I15, I16, I17, I19, I25	There is direct government support to lower the cost of capital, for example, through loan guarantees, direct equity stakes or low-cost capital from

(continued on next page)

Table 1 (*continued*)

	Identified threshold criteria	Interview Code	Examples to satisfy threshold criteria
			public investment bank (NEA OECD, 2022c). There is a secure and creditworthy economic structure (IAEA, 2024a). | The financing, ownership and risk allocation structures are acceptable to private investors (IAEA, 2024a). | SMRs can positively report against the environmental, social and governance (ESG) metrics (NEA OECD, 2022c).
Supply chain availability	Does the vendor have a credible strategy to achieve fleet deployment of the technology and expand the supply chain?	I03, I08, I10, I12, I14, I16, I18, I25	The vendor has several agreements in place with multiple countries, supporting the global deployment of its technology (NEA OECD, 2024). | There is evidence of sufficient SMR investments beyond the first project (IAEA, 2021a).
	Have the manufacturing and assembly facilities associated with the technology been established?	I03, I08, I10, I12, I13, I14, I16, I19	The project developer has raised significant capital to establish a complete module factory manufacturing environment (IAEA, 2021a). | The factory setup enables manufacturing and modularisation techniques, key to volume manufacturing (IAEA, 2021a).
	Have the supply chain capability and capacity been built and developed, respectively?	I03, I04, I06, I08, I10, I12, I16, I18	There are substantial investments in (1) building the capabilities required for advanced manufacturing and modularisation techniques, (2) developing a resilient supply chain for industrial components and systems, and (3) supporting the nuclear fuel pipeline (NEA OECD, 2022c; IAEA, 2022b). | There are formal partnerships in place between vendors and established suppliers and manufacturers to meet the demand (NEA OECD, 2024)
Commercial viability	Is the technology reliable?	I04, I08, I09, I11, I12, I14, I17, I25	The technology has been successfully validated through a reference project (NEA OECD, 2020; World Nuclear Association, 2021).

Table 1 (*continued*)

	Identified threshold criteria	Interview Code	Examples to satisfy threshold criteria
	Is the same technology design acceptable to regulators from different jurisdictions?	I01, I03, I05, I08, I10, I11, I12, I13, I14, I15, I21	The licensing and regulatory system is stable and predictable, enabling the standardisation of reactor designs in different jurisdictions (World Nuclear Association, 2020; NEA OECD, 2022a). | Safety evaluations and generic design certifications approved by a recognised competent authority to be accepted by equivalent authorities in other countries (World Nuclear Association, 2020).
	Is the technology cost-competitive against alternatives?	I01, I02, I03, I05, I08, I09, I10, I11, I12, I13, I15, I16, I17	The SMR projects have been significantly de-risked, attracting private capital at a value-for-money cost to consumers (NEA OECD, 2022c; IAEA, 2024a). | The technology has a mature design and a proven supply chain (NEA OECD, 2020). | There is confidence in the project being delivered on time and on budget (NEA OECD, 2024). | There is a reliable supply of fuel (IAEA, 2022b).

deployment. The regulatory bodies require the capability, especially for the non-LWR designs, and the capacity to support and assess the technology designs. *"They are dealing with new technologies they've never regulated before"* (I08). For example, the Terrestrial SMR have completed the Canadian pre-licensing review (Canadian Nuclear Safety Commission, 2018). One expert highlighted the extent of the challenge, noting, *"… at Terrestrial, they set off on a journey with the regulator seven or eight years ago, and they've only just gone through VDR Step 2, taking eight years to bring the regulator on that journey"* (I10). The process is time-consuming and requires substantial financial support to be completed. To further compound these challenges, the emerging technologies are increasingly being sited close to end-users yet, as one expert warns, *"there's very little understanding of what can go wrong, how it can go wrong, and what the consequences of that are going to be"* (I21), and the *"vendors are giving all the benefits without being open"* (I22) to potential issues and design limitations.

Most SMR developers *"are looking at traditional manufacturing techniques and probably are not pushing the boundaries of modularisation as much as possible"* with their FOAK designs (I06). The aspiration for the NOAK SMRs is to transition towards advanced manufacturing and modularisation techniques with significant end-of-line inspection and testing occurring across multiple factories in parallel. These advancements are expected to make the manufacturing and assembly process faster, more efficient, and reliable, while also enabling the use of higher-performance materials. The vision is *"to build everything in the factory, tested and commissioned"* (I10). Nevertheless, *"you'll still always need final permission on the site"* (I10). Several experts agree that an in-factory certification (Sam et al., 2023) can streamline the licensing process for SMRs. Specific components will become inaccessible as the assembly progresses within the factory, making early certification necessary to maintain a productive and uninterrupted manufacturing environment. It reduces the need for constant regulatory inspections. This approach will enable shifting *"much work in the factory to gather data and have the on-site more as the final confirmation step instead of starting from scratch"* (I03). However, a key challenge is that advanced techniques, such as *"advanced manufacturing, advanced inspection techniques, digitally enhanced techniques, application of AI in non-destructive examination and so on"* (I05), are not yet fully codified within the regulatory framework. If they have *"not been codified, then it will not be easy to do that in-factory certification"* (I05). Technology vendors are still collaborating with design code owners and regulators to gain approval for the relevant design codes.

3.2.3. Financial viability

There is no doubt that SMRs require a smaller capital investment relative to large reactors, making financing more achievable. As one expert noted, *"You're not trying to raise 20 billion; you're in the market trying to raise 2 billion"* (I13). While many interviewees share this view, they are also cautious about the FOAK units, as they do not yet have any financing advantages. One interviewee commented that *"the main difference compared to traditional NPPs is that SMR is still a theory"* (I09). Moreover, *"… the size of the financing package for each SMR might be outweighed by the fact that you then need a billion dollars to build a factory …"* (I14). This reflects concerns about high non-recurring engineering costs, particularly for establishing modular factory production and assembly. These upfront expenses are substantial and can only be offset through the "economies of multiples" gained from mass production in future units. It is also argued that the FOAK SMRs will be at a higher cost than LRs for the same capacity, leading one expert to question, *"Would lenders or investors want to take a worse deal because it's a smaller bite?"* (I04).

Producing long-term clean, secure, affordable, and diverse energy within a small footprint is crucial for societal progress. SMRs possess these attributes but are *"not appropriately valued in the conventional electricity markets"* (I04). The classic financial modelling of energy technologies principally concentrates on the costs and economics at a project level. For example, the Levelised Cost of Energy (LCOE) is a commonly used method for comparing the overall cost of generating electricity from different sources (Agar and Locatelli, 2020). However, the method focuses narrowly on the economic perspective, and subsequently, *"it massively skews the cost of nuclear on a forecast basis"* (I16). Another participant explained that the LCOE struggles to differentiate between firm and intermittent generating technologies, thus undermining the importance of baseload power. For instance, it does not capture the societal value of a small nuclear power plant compared to wind turbines that cover extensive areas. Additionally, its financial analysis fails to reflect the long-term operating life. As a result, the first wave of SMRs is not seen as economically competitive from an LCOE perspective.

The SMRs compete in a conventional electricity market where *"fossil fuel plants have an implicit subsidy"* (I15), as they are not required to pay for the carbon they emit. Several interviewees highlight providing various subsidy assistance to enhance the economic competitiveness of SMRs in the market and implement cost recovery mechanisms, guaranteeing revenue stability and certainty for these longstanding assets. Governments can underwrite the FOAK risks associated with SMRs as *"equity investors, loan guarantors or insurers of last resort"* (I09). *"For these initial projects, government* funding *will probably be the most likely source to provide the initial financing round because there is too much risk"* (I11). This support lowers the cost of capital and helps achieve a competitive energy cost in conventional electricity markets.

However, government-led interventions cannot solve all barriers to investments. The involvement of private investment is crucial to the success of SMR projects. Several interviewees believe that partnerships between SMR developers and multilateral financing institutions or organisations with solid balance sheets and strategic interests in nuclear power are essential. They added that another enabling factor is building a strong consortium that includes experienced nuclear operators, established suppliers with reliable supply chains, and reputable contractors known for their delivery capability. One expert expanded on the potential partnerships: *"Either partner up with a large state-owned utility, and you can see that happening in Canada, right with OPG or New Brunswick Power, or you find some very deep-pocketed entrepreneur like Bill Gates* (TerraPower)*, or you're a division of a very large corporation like Bechtel or Fluor and NuScale"* (I14). A strong ownership structure and an experienced project delivery team significantly mitigate project risks and give investors confidence that the project can be delivered within the agreed schedule and budget.

Presently, private finance faces its own set of hurdles. One expert noted that *"challenges in financing today are that most financial institutions don't have much nuclear experience"* (I18) to assess such projects. This expertise gap creates a financing bottleneck that one interviewee believes could be relieved by *"establish[ing] a large multilateral institution that would have … experts able to review nuclear projects, whether they're larger reactors or SMRs, act as a reference to select projects that they would accept to finance, and then attract other financiers into financing nuclear power"* (I25).

3.2.4. Supply chain availability

The current landscape of SMRs is saturated with potential vendors, creating more confusion than progress. One expert stated, *"One of the problems with SMR is there are too many options out there right now, and you have to sort of triage them and get down to a few who are really credible"* (I12). The overwhelming number of SMR vendors creates a false impression of a large market with numerous viable designs when, in fact, deploying only a few designs in large quantities to dominate each market niche can lead to benefitting from "economies of multiples". The research and development costs for SMRs are significant, making it unrealistic to expect comprehensive support from the public and private sectors for all designs. However, if a selected design is deployed across multiple sites, *"then a lot of those front-end costs of engineering design and procurement will be amortised over a larger number"* (I24). Additionally, regulatory bodies may not have the capacity to review multiple technologies simultaneously. Therefore, selecting a limited number of viable SMR designs will enable the host countries to provide the relevant support.

The first vendors of SMR technology to successfully deploy their products to the market will have a competitive advantage. This will enable them to secure more investments than later ones and strengthen their position to achieve fleet deployment in both domestic and international markets. Those investments enable SMR vendors to establish their supply chains and manufacturing facilities, thereby expanding their capabilities and capacities. *"The best way to ensure that you don't run into major supply chain issues and scaling issues is to have a firm order book upfront"* (I16), added an expert. *"The best technology may not win"* (I15), but the ones with the strongest financial support, higher technological maturity, and reduced risks associated with their deployment are seen as most attractive to investors. They are likely to get that early mover advantage and establish a leading market position.

The proposed business model by the SMR vendors is another important selling point. *"It's got to be volume production"* (I08), highlighted this expert. From an investment standpoint, the investors want a business model where the vendors *"are taking a huge amount of risks, be it construction or operating risks. It's a new reactor that is very risky and is in a new market for SMRs"* (I08). Moreover, the SMRs are attractive not only to utility companies but also to energy-intensive industrial users and data server companies. These industrial users and data server companies lack the prerequisite operational capability. They are looking for models where the vendors assume complete responsibility for their products throughout their life cycle. The vendors retain ownership of their plants and the associated risks and generate revenue through power purchase agreements.

3.2.5. Commercial viability

The transition to private investment is contingent on the bankability of energy projects. *"At present, no SMR is at the level of commercialisation – none of them!"* (I25). Validating the technology by deploying a fully operational reference is an important milestone. There is significant cautiousness around the technology, but *"once you build a representative SMR and show that it is deliverable, there's no doubt that investors will be interested. This isn't isolated to SMRs"* (I17). Demonstrating that the project can be delivered within the established schedule and cost aids in securing further investments and scaling up the commercial production of SMRs. It will also strengthen political and public support for the technology. Potential investors need assurance that those projects are bankable and viable in the long term.

The interview results suggest that significant front-end planning is necessary to establish a realistic budget and schedule for a project. An expert highlighted that *"creating believable, supportable dates is very important right now in the industry"* (I12). Effective planning maintains credibility, whereas insufficient preparation can jeopardise the entire programme. The FOAK projects involve higher costs and extended timelines than the NOAK projects. They will likely incur several one-off costs and face increased risks, necessitating more contingency planning.

While it is conceivable to the interviewees that the regulators may take significant time to license the FOAK SMRs, the expectation is that the subsequent SMRs sharing similar designs will benefit from "economies of multiples", leading to a faster and more efficient regulatory approval process. The regulators will be familiar and comfortable with the design. As such, the licensing of the SMR designs becomes straightforward, predictable and reproducible, with exceptions to the site-specific changes. This will significantly influence the financing of SMRs, *"for example, if the licensing process is smooth, we could witness an earlier start of construction and the first concrete date, which would be a financial advantage for the SMR"* (I07).

"There is a definite advantage in reducing the build time and cost and achieving potentially higher quality" (I21) as the SMRs benefit from learning efficiencies and focus on standardisation, modularisation, and factory manufacturing, with minimal work carried out on-site. According to the interviewees, building confidence in project delivery extends to establishing a strong supply chain acceptable in multiple jurisdictions, adopting advanced manufacturing techniques to ramp up delivery, developing workforce capability and capacity and having a reliable fuel supply chain. As these areas become more apparent and the designs gain maturity, SMRs are expected to be commercially driven by the global market demand. One interviewee added that *"the commercial model should be all about delivering affordable electricity"* (I02) without relying on subsidies. The private sector will be more inclined to invest in SMRs.

4. Discussion

4.1. Novelty and contribution of the framework

While the five dimensions identified in this study, namely (1) policy support, (2) licensing and regulatory readiness, (3) financial viability, (4) supply chain availability, and (5) commercial readiness, have been individually explored in prior energy literature (Locatelli et al., 2014; Mignacca et al., 2020; NEA OECD, 2021; Sam et al., 2023), the unique contribution of this research lies in integrating these dimensions into a single operationalised framework that allows for systemic measure of progress in SMR deployment.

First, the framework moves beyond qualitative description by introducing objective, threshold-based criteria framed as simple "yes/no" questions. Such binary operationalisation represents a valid abductive strategy to simplify complex realities into practical and measurable forms (Timmermans and Tavory, 2012). The design enables clear, consistent assessment across projects, reducing the subjectivity often associated with evaluating the development of emerging technologies.

Second, the framework addresses the interdependence among the five dimensions, recognising that progress in one area is insufficient unless matched by advancement in others. Unlike previous studies that treat these areas in silos, this research conceptualises SMR commercialisation as a systemic process where bottlenecks in any domain can stall overall progress.

By operationalising systemic progress into measurable, practical indicators, this framework provides scholars and practitioners with a novel tool for identifying bottlenecks, measuring progress, and accelerating the deployment of SMRs. It advances the field from broad narrative descriptions of challenges and barriers to a structured, actionable approach for supporting complex energy transitions.

4.2. Comparison with existing frameworks

The deployment of SMRs presents a critical opportunity to replicate aspects of the successful transitions in renewable energy technologies such as solar and wind. Over the past few decades, these technologies have benefited from substantial policy support, strategic investment incentives, and the progressive achievement of economies of scale, making them viable alternatives to fossil fuels (Ang et al., 2022). SMRs now stand at a similar point; however, their pathway to commercialisation is shaped by additional complexities specific to the nuclear sector.

A notable similarity between the developed framework and those applied to renewable energy technologies is the emphasis on policy support and economic viability. The literature consistently highlights that the rapid growth of renewables was underpinned by a mix of technology-push policies, such as R&D investment, and market-pull measures, such as deployment subsidies (Corsatea et al., 2014; Best and Burke, 2018). For instance, China's significant expansion of wind power followed the enactment of the "Renewable Energy Law," providing a robust legislative foundation for sector growth (Dai et al., 2018). Similarly, in the case of the nuclear power programmes, strong national commitment facilitated successful fleet deployment in countries such as France and South Korea (Choi et al., 2009; Grubler, 2010). Reflecting these lessons, the policy support for SMRs must go beyond securing initial government endorsement to ensuring resilience over time and alignment with long-term environmental objectives, a challenge that fossil fuel projects are now dealing with (Papadis and Tsatsaronis, 2020).

Achieving commercial viability for SMRs, like for renewables, requires not only significant upfront investment but also the ability to deliver reliable, cost-competitive energy solutions at scale. The experiences from the wind and solar sectors demonstrate the importance of coordinated policy and investment frameworks to reach widespread commercial adoption (Corsatea et al., 2014; Gielen et al., 2019). This reinforces the importance of systemic alignment across policy, regulation, finance, and supply chains captured within the SMR framework.

However, important differences distinguish SMRS from the renewable energy trajectory. Unlike renewables, SMRs face significantly greater regulatory complexity, with licensing pathways often fragmented across jurisdictions (Sainati et al., 2015; Sam et al., 2023). This regulatory uncertainty threatens the ability to replicate standardised designs across markets and achieve the "economies of multiples" critical for cost reduction, as seen in renewable energy projects like wind and solar (Gielen et al., 2019). The lack of a unified regulatory approach increases the complexity and risk associated with SMR projects, potentially deterring investment and slowing deployment.

Moreover, the financial landscape for SMRs is notably different from that of renewable energy projects. To date, no fully modular SMR units have been constructed, which further complicates financing at this early stage of development (Mignacca et al., 2018; Nian et al., 2022). While project financing is commonly used in most energy infrastructure projects, it is not the norm in the nuclear sector due to the substantial upfront investment required and the inherent risks associated with nuclear technology (Barkatullah and Ahmad, 2017; Sainati et al., 2019). Until recently, nuclear energy had been mainly excluded from support by major multilateral development banks (MDBs) like the World Bank, further complicating the financial landscape of SMRs (Sauer et al., 2022). However, in mid-2025, the World Bank's board approved a policy shift to allow financing of nuclear new build, SMRs and refurbishment of existing reactors, marking a significant change in international financing conditions (World Bank, 2025). The impact of this shift is still emerging. It remains uncertain which countries will be able to access this funding, to what extent it will mitigate risks for private investors, and how quickly these new channels will influence SMR financing globally. This uncertainty highlights the ongoing need for innovative financial mechanisms and robust government support to attract private investment and address the risks associated with SMR projects.

The scale of modularisation and manufacturing associated with SMRs can be compared to industrial chemical plants and off-site modular construction industries (Wrigley et al., 2024). SMRs face significant financial and logistical challenges in establishing a manufacturing and assembly environment capable of producing modular nuclear components (Mignacca et al., 2020). Furthermore, the supply chain is complex; highly specialised components and materials with nuclear-graded labels are required to meet the stringent quality and safety standards and a stable and secure fuel supply (NEA OECD, 2020; NEA OECD, 2021). Developing a robust and resilient supply chain is critical to ensuring the scalability and reliability of SMRs.

5. Conclusion

There is substantial interest in deploying SMRs due to their potential to address the energy trilemma by providing reliable, low-carbon, and affordable energy. However, SMRs remain an emerging technology, with most designs still in the conceptual stage compared to proven technologies like LRs.

This study developed a systemic framework to assess the progress of SMRs towards commercial deployment. Integrating five critical areas, namely, policy support, licensing and regulatory readiness, financial viability, supply chain availability, and commercial readiness, into an operationalised framework provides a practical tool to identify potential bottlenecks and measure systemic progress. The research findings highlight that SMR deployment is not a purely technological challenge, but a systemic one which requires coordinated advancement across the five main areas identified. While each area has been explored individually in prior literature, this study's contribution lies in synthesising them into an actionable framework that captures their interdependence.

The research acknowledges certain limitations. First, using purposive and snowball sampling may introduce selection bias, potentially over-representing the views of stakeholder groups most deeply engaged in SMR deployment. Although data triangulation with secondary sources was employed to mitigate this risk, the inherent subjectivity of expert perspectives cannot be fully eliminated. Furthermore, the perspectives gathered primarily reflect the contexts of established nuclear countries, which may limit generalisability to emerging economies or newcomer nuclear markets.

Future work should focus on empirically applying and refining the framework through case studies of SMR projects and comparable technologies. Further research could also explore prioritising and sequencing the enabling elements identified to optimise SMR programme implementation. By offering a structured and adaptable tool for assessing systemic readiness, this framework contributes theoretically and practically to advancing the deployment of innovative low-carbon energy solutions.

CRediT authorship contribution statement

Rohunsingh Sam: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tristano Sainati:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Robert Kay:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Timothy Cockerill:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Profile of the Interviewees

Table 2
Profile of the interviewees

Interview Code	Expertise Area(s)	Years of Experience	Interview Duration
I01	Technical	20+	40 min
I02	Financial	20+	45 min
I03	Technical and financial	10+	50 min
I04	Financial	30+	55 min
I05	Technical	30+	40 min
I06	Technical	20+	55 min
I07	Technical	10+	25 min
I08	Technical and financial	30+	45 min

(*continued on next page*)

Table 2 (*continued*)

Interview Code	Expertise Area(s)	Years of Experience	Interview Duration
I09	Financial	10+	55 min
I10	Technical	10+	65 min
I11	Financial	30+	55 min
I12	Legal and financial	20+	50 min
I13	Financial	20+	50 min
I14	Financial	20+	25 min
I15	Financial	30+	60 min
I16	Financial	10+	50 min
I17	Financial	20+	60 min
I18	Financial	30+	60 min
I19	Technical	10+	50 min
I20	Legal and regulatory	10+	40 min
I21	Legal and regulatory	30+	70 min
I22	Legal and regulatory	10+	60 min
I23	Legal and regulatory	30+	30 min
I24	Technical and financial	20+	50 min
I25	Financial	20+	40 min

Appendix B. Example of the coding process

Table 3
Example of the coding process

Aggregate Dimension	2nd-order Themes	Representative 1st-Order Quotes
Policy support	Lack of early-stage financing is stalling commercial efforts	*"The biggest challenge to me is how you get from where you are today to commercial final investment decision."* (I17) *"… too early to talk about any financing advantage."* (I14)
	Government support is critical to creating an enabling environment	*"At the outset of developing a nuclear programme, you need to have a governmental framework that authorises the use of the technology."* (I23) *"Policy support needs to be set, followed by the nuclear law framework."* (I20) *"Ultimately, failure of the electric system, if the lights are not on, the government bears the policy risk."* (I14)
	Private investors need visibility on the market for SMRs	*"The challenge here is that SMRs into deployment feels up to 10 years away. This is the problem for investors who are looking for immediate opportunity."* (I17) *"Would lenders or investors want to take a worse deal because it's a smaller bite?"* (I04)

Data availability

The data that has been used is confidential.

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