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Review

Licensing small modular reactors: A state-of-the-art review of the challenges and barriers

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ABSTRACT

Small Modular Reactors are gaining significant interest for their reduced footprint, lower power output, modularity, and innovative features. The licensing of SMRs is key to their successful deployment. However, the literature on this subject area is limited and often fragmented among other characteristics of the SMRs, thus failing to address the licensing aspects distinctly. The paper employs a systematic literature review to identify the potential nuclear licensing barriers and challenges that can influence the deployment of SMR and to provide an overview of their implications. The authors differentiate between licensing barriers and challenges as follows. The licensing barriers are likely to affect the deployment of SMRs for over a decade and necessitate the collaboration of multiple organisations. The licensing challenges can be resolved within ten years and can be led by a single organisation to deliver the solution. The licensing barriers are: (1) existing legal and regulatory framework; (2) prescriptive regulatory framework; (3) novelty in the technology; (4) regulatory fragmentation; and (5) absence of in-factory certification. The licensing challenges are: (1) fees charged by regulators; (2) regulatory capability gaps; and (3) lengthy licensing duration. The identified barriers and challenges have implications on the project timeline and cost, consequently affecting the overall economics of the SMR.

1. Introduction

The climate change, energy security and affordability crises are at the nucleus of many important discussions (World Nuclear Association, 2022; IAEA, 2022b). There is an increasing urgency to act on those crises, and the failure to mitigate them can cause profound ramifications. Most of the ongoing conversations on this subject converge towards a shift from fossil fuels to low-carbon and reliable energy sources, such as nuclear (Saidi and Omri, 2020; Mathew, 2022; Nian et al., 2022; Sadiq et al., 2023). It is one of the lowest emitters of greenhouse gases compared to other low-carbon sources and is highly reliable (IAEA, 2021a). However, large nuclear energy projects are also associated with financial and safety risks due to construction, technical, operational, and political factors (Locatelli, 2018; Testoni et al., 2021).

Over the years, there has been a keen and increasing global interest in a newer generation of reactors termed small modular reactors (SMR) (Carelli et al., 2010; Ramana et al., 2013; Locatelli et al., 2014; Hidayatullah et al., 2015; Sainati et al., 2015; Vegel and Quinn, 2017; Mignacca et al., 2020). SMRs have a smaller plant footprint than conventional nuclear power plants (NPP) and are modular. Their components and systems are manufactured in a factory-controlled environment and then transported to the nuclear site for installation (Mignacca et al., 2019; IAEA, 2022d). The SMRs are characterised as (1) nuclear reactors having a capacity of less than 300MWe or less than 1000 MW t per reactor; (2) reactors designed for commercial use unlike research and test reactors; (3) plant which can closely accommodate multiple reactors to the same infrastructure; (4) light water reactor (LWR) or non-light water reactor (non-LWR) technology; and (5) certain reactors having unconventional features that are not well-known to regulators (SMR Regulators Forum, 2018).

The SMR technologies are heterogeneous, with more than 80 designs at different phases of development (IAEA, 2022a). SMR offers many benefits, as highlighted by Hidayatullah et al. (2015) and Carless et al. (2019). The design simplicity, through novel technologies, offers enhanced safety and security. The modular design introduces construction efficiency and increases the reliability of the finished products through improved quality control. It is also more suited for the economy of mass production and lowers the initial capital investment. Lower

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capital costs lead to shorter payback periods and reduced financial risk (Locatelli et al., 2014). Modularisation can reduce construction schedules and cost overruns (Boarin et al., 2012; Mignacca et al., 2018). In addition to electricity generation, the SMRs can also be used for co-generation, such as industrial process heat applications, district heating, hydrogen production, and desalination (Hidayatullah et al., 2015; Locatelli et al., 2017). However, despite all these attractive features, only the People's Republic of China has been able to construct a land-based SMR, a High-Temperature Gas-Cooled Reactor - Pebble-bed Module (HTR-PM) (World Nuclear News, 2021). The 27MWe Central Argentina de Elementos Modulars (CAREM) in Argentina and China's 125MWe ACP100 are the other two SMRs currently under construction (IAEA, 2022e).

This limited number of SMRs in operation subsequently questions the ability of these emerging reactors to cope with nuclear licensing. The licensing of NPPs has a more significant role in regulatory control (Bredimas and Nuttall, 2008; Sainati et al., 2019). The principal actors in a nuclear licensing process are the regulatory authority, which evaluates if all the applicable safety, security and other licensing criteria are satisfied, and the applicant, who shows compliance with the relevant nuclear safety requirements (Bredimas and Nuttall, 2008). The other stakeholders involved, among others, include the technical support organisation (TSO) that assists the regulator, the SMR vendor or supplier that supports the applicant, the government through policy-making, the public through consultation processes with regulators, and the law courts in case of appeals (World Nuclear Association, 2015b; NEA OECD, 2022b).

The prevailing licensing systems in most countries with nuclear power programmes have been designed and operated in the context of large nuclear reactors (Ramana et al., 2013; Sainati et al., 2015). Existing traditional nuclear licensing processes are lengthy in duration, high in cost, and adoptive of conservative and stringent regulatory requirements (Mignacca et al., 2020). Applying the same established licensing process to SMR can be very challenging. SMRs with LWR technology are more likely to face fewer hurdles than non-LWR technology because they will use a nuclear infrastructure similar to LWR large reactors (LRs) (Atkins and EY, 2016). Nonetheless, they are all expected to come across different licensing problems that may prevent certain benefits of SMRs from being achieved.

Although nuclear licensing is one of the first and most crucial processes in deploying a SMR, there is limited research concerning this topic in nuclear journals. Most of the literature on SMRs concentrates on the technical aspects; only a few authors have focused exclusively on licensing SMRs (Ramana et al., 2013; Sainati et al., 2015). Other authors have briefly discussed them in academic journals and non-peer reviewed industry publications. Consequently, much of the relevant information on the licensing of SMR has been scattered across the different publications. It is essential to bring together the literature on nuclear licensing, considering that SMRs are gaining significant momentum and licensing has a major influence on deployment.

This paper employs a systematic literature review (SLR) approach to identify and discuss how nuclear licensing affects the deployment of SMRs. The scope of the research focuses exclusively on the impact of deploying the SMR projects from a project management perspective.

The outcome of this paper will clarify the role of nuclear licensing in deploying SMR and informing the key stakeholders such as the policymakers, investors, vendors, operators and regulators. The findings also pave the way for further research on this subject. The rest of the paper is structured as follows. Section 2 details the research approach adopted to conduct the systematic literature review. Section 3 and Section 4 present and discuss the research findings on how licensing influences the deployment of a SMR. Section 5 concludes the research paper and includes the policy implications and suggestions for future works emerging from the analysis.

2. Research approach

This paper covers a systematic literature review to obtain relevant academic articles from Scopus (search conducted in April 2023) and reports from key institutions such as the International Atomic Energy Agency (IAEA), Nuclear Energy Agency - Organisation for Economic Cooperation and Development (NEA-OECD) and World Nuclear Association (WNA) (search conducted in April 2023). The reports published by national laboratories were outside the scope of this research. The academic articles and institutional reports provide a comprehensive global overview of nuclear licensing issues. Nonetheless, it is essential to acknowledge that there can be inherent industry bias in the information sources. The SLR approach allows the authors to provide a comprehensive perspective of the research objectives and is detailed enough to enable the reproducibility of the works (Mignacca and Locatelli, 2020a). The data collection is split into two streams: firstly, academic articles and secondly, institutional reports.

2.1. Literature from academic articles

We employed the following research steps for the review process.

a) The keywords pertaining to the research objectives and their synonyms commonly used in literature were identified for the Scopus search (see the list in Appendix A) and combined using Boolean operators. The functions "TITLE" and "ABS" were applied on the advanced search option of the Scopus website to ensure that the above-identified keywords were featured in the titles or the abstracts of the documents. The Scopus search string was as follows:TITLE-ABS(("SMR" OR "Small Modular Reactor*" OR "Small Modular Nuclear Reactor*" OR "Small Medium Reactor*" OR "Advanced Modular Reactor*" OR "Gen* IV Reactor*") AND ("Nuclear") AND ("Licen*" OR "Permit*" OR "Authorisation" OR "Regulat*" OR "Law*" OR "Legal*" OR "Legislation*" OR "Statute*" OR "Treat*" OR "Convention*" OR "Standards" OR "Prescriptive based" OR "Performance-based" OR "Goal Setting" OR "Emergency Planning Zone" OR "EPZ" OR "Safe*" OR "Security" OR "Defence-in-Depth" OR "DiD" OR "Graded Approach") AND ("Challeng*" OR "Barrier*" OR "Obst*" OR "Constrain*" OR "Complica*" OR "Difficult*" OR "Issue*" OR "Impediment*" OR "Problem*" OR "Novel*" OR "Limit*"))
b) The search returned 459 results. The authors applied two exclusion criteria: (1) The articles are not written in English, and (2) The articles are not classified as 'Journals' according to the Scopus website. It resulted in 187 documents.
c) Their titles and abstracts were analysed according to the following inclusion criteria: the articles must focus on the subject of deployment of the SMRs. The number of papers was refined to 50.
d) The papers were reviewed to identify potential licensing issues. During the in-depth reading, 17 papers were discarded because they did not meet the scope of the current research. The appropriate information was extracted from the remaining 33 papers. Table 1 shows the licensing issues and the references of the academic articles for each issue.

2.2. Literature from institutional reports

For the institutional reports, we employed the following steps.

(a) The first stage involved customising our keyword searches according to the website functionality of the institute. The authors applied exclusion criteria: (1) The reports are not written in English, and (2) The reports were published before 2000.

The IAEA has a publication platform (www.iaea.org/publications) where important scientific and technical resources are uploaded. The

Table 1
Licensing issues and references of the academic articles.

Licensing Issues	References – Academic Articles
Existing Legal and Regulatory Framework	(d'Oro and Golay, 2012; Hidayatullah et al., 2015; Sainati et al., 2015; Siegel et al., 2018; Mignacca et al., 2020; Testoni et al., 2021; Liu et al., 2023; Black et al., 2023)
Prescriptive Regulatory Approach	(Zhang and Sun, 2007; Kuznetsov, 2008; Kim et al., 2010; Ramana et al., 2013; Söderholm et al., 2014; Hidayatullah et al., 2015; Sainati et al., 2015; Carless et al., 2019; Hussein, 2020; de la Rosa Blul, 2021)
Novelty in the Technology	(Laina and Subki, 2012; Ramana et al., 2013; Cooper, 2014; Oh et al., 2014; Hidayatullah et al., 2015; Sainati et al., 2015; Aydogan et al., 2015; Zinkle et al., 2016; Magwood and Paillere, 2018; Budnitz et al., 2018; Hussein, 2020; Liu et al., 2023; Black et al., 2023)
Regulatory Fragmentation	(Ramana et al., 2013; Söderholm et al., 2014; Iyer et al., 2014; Oh et al., 2014; Hidayatullah et al., 2015; Sainati et al., 2015; Playbell, 2017; Budnitz et al., 2018; Thomas, 2019; Zeliang et al., 2020; Schaffrath et al., 2021; Lloyd et al., 2021; Nian et al., 2022; Liu et al., 2023)
Absence of In-factory Certification	(Sainati et al., 2015; Mignacca and Locatelli, 2020b; Lloyd et al., 2021)
Fees charged by regulators	(Locatelli et al., 2014; Cooper, 2014; Vegel and Quinn, 2017; Mignacca et al., 2020).
Regulatory Capability Gaps	(Ramana et al., 2013; Mignacca et al., 2020; Black et al., 2023; Nian et al., 2022
Lengthy Licensing Duration	(Bredimas and Nuttall, 2008; Ramana et al., 2013; Sainati et al., 2015)

authors restricted the keywords searches to *"Small Modular Reactor"* and *"Nuclear Licensing"* and applied the above exclusion criteria. 47 publications from the IAEA platform were retrieved in total. The authors identified 9 additional documents on the IAEA website in the Small Modular Reactor Regulators' Forum section.

The NEA-OECD website (https://www.oecd-nea.org/) has a search platform that enables easy access to its extensive topics and resources. The authors limited the search to "NEA Document" and "Publications and Reports" by selecting these two options in the "By resource" drop-down list. The same keyword searches and exclusion criteria for the IAEA were applied. 31 publications from the NEA-OECD platform were retrieved in total.

Concerning the WNA, there was no search option specific to the publication platform on their website. The authors limited the document retrieval to the Cooperation in Reactor Design and Licensing (CORDEL) Working Group Reports (https://world-nuclear.org/our-association/publications/online-reports.aspx), where 43 documents were reviewed in total.

(b) In the second stage, the titles, executive summary/foreword, introduction and conclusion of the documents were analysed according to the following inclusion criteria: the documents must focus on deploying the SMRs. 45 documents satisfied the criteria (17 from IAEA, 13 from NEA-OECD and 15 from WNA CORDEL).
(c) In the final stage, the remaining documents were reviewed in depth. The authors identified 22 relevant documents (8 from IAEA, 2 from the IAEA SMR Regulators' Forum, 6 from NEA-OECD and 6 from WNA CORDEL). Table 2 shows the licensing issues and the references of the institutional reports for each issue.

2.3. Analysis and conceptualisation

In Section 3 and Section 4, the authors critically analysed the existing literature on licensing SMRs to identify the licensing issues and their implications on the deployment of SMRs. The unit of analysis used to identify the licensing issues was rationalised as follows. The authors focus on discussing all issues associated with licensing SMRs. Whenever comparisons were made against LRs, it was used as a benchmark to emphasise the extent of the licensing issues in SMRs. All the final retrieved academic journals and institutional reports were exported to NVivo, a qualitative data analysis software. The relevant information was extracted from these journals and reports. The authors coded inductively the relevant statements according to the identified licensing issues. In addition to the bulk of the literature, the authors have considered additional spare readings from nuclear regulatory authorities' websites. They were introduced as bespoke examples to give a better understanding of the licensing issues described below.

Table 2
Licensing issues and references of the institutional reports.

Licensing Issues	References – Institutional Reports
Existing Legal and Regulatory Framework	(World Nuclear Association, 2015a; IAEA, 2017; SMR Regulators Forum, 2018; NEA OECD, 2019; NEA OECD, 2020; NEA OECD, 2021b; IAEA, 2021b; World Nuclear Association, 2021a; IAEA, 2022d)
Prescriptive Regulatory Approach	(World Nuclear Association, 2008; IAEA, 2013; World Nuclear Association, 2015a; NEA OECD, 2016; IAEA, 2018a; SMR Regulators Forum, 2018; NEA OECD, 2020; IAEA, 2021b; SMR Regulators Forum, 2021; NEA OECD, 2022a; IAEA, 2022c; IAEA, 2022d)
Novelty in the Technology	(World Nuclear Association, 2015a; NEA OECD, 2016; IAEA, 2017; IAEA, 2018b; SMR Regulators Forum, 2018; NEA OECD, 2019; NEA OECD, 2020; NEA OECD, 2021b; IAEA, 2021b; SMR Regulators Forum, 2021; World Nuclear Association, 2021a; World Nuclear Association, 2021b; IAEA, 2022c; NEA OECD, 2022a; IAEA, 2022d)
Regulatory Fragmentation	(World Nuclear Association, 2008; World Nuclear Association, 2015a; World Nuclear Association, 2015b; IAEA, 2018a; SMR Regulators Forum, 2018; NEA OECD, 2020; World Nuclear Association, 2020; NEA OECD, 2021b; World Nuclear Association, 2021a; World Nuclear Association, 2021b; NEA OECD, 2022a)
Absence of In-factory Certification	(World Nuclear Association, 2015a; NEA OECD, 2016; IAEA, 2018b; NEA OECD, 2021b; SMR Regulators Forum, 2021; IAEA, 2022c; IAEA, 2022d)
Regulatory Capability Gaps	(NEA OECD, 2017; NEA OECD, 2019; NEA OECD, 2020; IAEA, 2021b; NEA OECD, 2021b; SMR Regulators Forum, 2021; World Nuclear Association, 2021a; NEA OECD, 2022a
Lengthy Licensing Duration	(World Nuclear Association, 2015b; NEA OECD, 2017; IAEA, 2017; SMR Regulators Forum, 2018; IAEA, 2021b; NEA OECD, 2021b; World Nuclear Association, 2021a; NEA OECD, 2022a)

Moreover, we have employed a conceptual framework to distinguish between the relevance of the licensing issues. We have classified the licensing issues into licensing barriers and licensing challenges. We differentiate between the terms "barriers" and "challenges" from a timeframe and ownership perspective, as shown in Table 3.

The licensing barriers refer to obstacles that are very difficult to overcome and are likely to affect the deployment of SMRs for over a decade. A consortium of organisations must collaborate to deliver solutions. An environment involving several organisations is complex and time-consuming, as they should all be in agreement to resolve any issues. The licensing challenges require significant effort to overcome, but they

Table 3
The threshold criteria to distinguish between barrier and challenge from a timeframe and ownership perspective.

Timeframe to resolve licensing issues	Ownership of the licensing issues	Outcome
More than ten years	Consortium of organisations	Barrier
Within ten years	Led by a single organisation	Challenge

can be resolved within ten years. A single organisation is involved in leading the delivery of the solution, which is a less complex environment than multiple organisations. The authors recognise that it is an arbitrary choice to use a ten years timeframe. The rationale is that such a timeframe is realistic for an existing nuclear programme under development as opposed to a significantly long timeframe that is not necessarily something that can be implemented.

Furthermore, by classifying licensing issues into licensing barriers and licensing challenges, stakeholders in the SMR industry can have a clearer understanding of the most critical licensing issues that may impact the deployment of SMRs. Such an approach enables them to identify and prioritise licensing issues. They are better positioned to allocate resources more effectively and develop targeted strategies to overcome the identified barriers and challenges.

3. Licensing barriers

3.1. Existing legal and regulatory framework

The present legal and regulatory framework has been designed and operated for LRs (Sainati et al., 2015), so the innovative attributes of the wide range of SMR designs are most likely to challenge the current framework (SMR Regulators Forum, 2018). It can unfold into legal issues which may impede the deployment of SMRs (NEA OECD, 2021b). For example, SMRs contain passive systems, integral designs and reduced failure modes, which can enhance their safety and economic performance (IAEA, 2017; NEA OECD, 2019; IAEA, 2021b; World Nuclear Association, 2021a). Equally, these features deviate significantly from traditional regulatory and licensing expectations (Liu et al., 2023; Black et al., 2023). D'Oro and Golay (2012) and Siegel et al. (2018) emphasised that further regulatory efforts should be in place to assess the proliferation resistance in the case of SMR designs. If not, protecting the fuel material in the reactor core would be very challenging when the SMRs are deployed in large quantities and in secluded areas (Siegel et al., 2018). There is also the cyber security issue linked to the off-site remote operation of SMRs (Hidayatullah et al., 2015; Testoni et al., 2021; Black et al., 2023). The NEA-OECD thinks that SMRs can be treated as low-risk installations if the applicable conventions and national laws allow for that. It will considerably reduce the nuclear liability and insurance amount the nuclear operators must pay (NEA OECD, 2021b). Nuclear liability and insurance are long-term costs incurred, and such difference significantly impacts the project's financing framework (NEA OECD, 2020). Therefore, the existing framework may necessitate adaptations or a new framework has to be developed to address the deviations in the established licensing process (Hidayatullah et al., 2015; Sainati et al., 2015; Testoni et al., 2021; IAEA, 2022d; Liu et al., 2023; Black et al., 2023).

The authors frame the existing legal and regulatory framework as a barrier to the licensing of SMRs. Such frameworks are implemented by the national authorities and are derivatives of national laws. Reforming the existing frameworks in the case of nuclearised countries, that is, countries with nuclear power programmes or developing new frameworks in the case of newcomer countries, are complex and laborious processes. From a national perspective, multiple organisations, such as the parliament, nuclear regulatory authority and various ministries, must be involved in delivering a solution. Such interventions take substantial time to materialise (World Nuclear Association, 2015a; IAEA, 2017; Mignacca et al., 2020).

3.2. Prescriptive regulatory approach

There are two main regulatory approaches – prescriptive-based and goal-setting, commonly known as performance-based (Söderholm et al., 2014; Sainati et al., 2015). The prescriptive approach is rigid because it mainly contains detailed and measurable requirements that the reactor design must comply with (World Nuclear Association, 2008; World Nuclear Association, 2015a; IAEA, 2021b). It is an efficient licensing process for proven and standardised nuclear reactor technologies (Sainati et al., 2015).

Conversely, applying such a prescriptive approach to the first-of-a-kind (FOAK) SMRs could result in overregulation (NEA OECD, 2022a). The safety risk profile of SMRs differs from the LRs, as it is limited to factors such as smaller power output, reduced radioactive inventory, passive safety systems and underground location of the reactor vessels for enhanced protection against hazards (Carless et al., 2019).

The goal-setting approach is technology-neutral and risk-informed (Kim et al., 2010; Hussein, 2020). It is thus ideal for dealing with innovative and novel SMR features where uncertainties must be addressed, and supplementary measures or margins may be required (SMR Regulators Forum, 2018). Instead of pre-defined norms for the FOAK designs, the regulators use the principles of a graded approach to establish overall performance goals for the SMR in the form of numerical risk targets (World Nuclear Association, 2015a; IAEA, 2018a; SMR Regulators Forum, 2018; IAEA, 2022c). The risks are kept as low as reasonably achievable (ALARA) or as low as reasonably practicable (ALARP).

The SMR developers advocate for a reduced emergency planning zone (EPZ). It refers to a buffer area around NPPs designated for implementing the necessary operational and protective measures in a nuclear emergency (SMR Regulators Forum, 2018; IAEA, 2021b; de la Rosa Blul, 2021). Under a prescriptive regulatory approach, the current NPPs are licensed with a traditionally large EPZ radius (IAEA, 2013). Applying the same large EPZ radius to the SMRs is ineffective. The NuScale SMR developers, using a goal-setting approach, proposed a sizing methodology to assess the EPZ size of their plant design. Their proposal was deemed a technically adequate method and has been approved by the United States Nuclear Regulatory Commission (US NRC) (US NRC, 2022). Moreover, a smaller EPZ radius significantly reduces its overall set-up and maintenance costs, thus further enhancing the economic prospects of the SMR (Zhang and Sun, 2007; Ramana et al., 2013; Carless et al., 2019). Carless et al. (2019) estimate that an NPP with a 40-year lifetime can save nearly $50 million by reducing its EPZ radius to 5 miles. Moreover, a SMR with co-generation products should be ideally located close to both the targeted end users and the SMR plant to be economically feasible (IAEA, 2013).

Equally, applying a prescriptive approach designed for LRs on SMRs leads to a high staff requirement in the control rooms or an increase in the number of control rooms. This can, in turn, impact the plant operation and maintenance costs, affecting the economic capability of the SMR (Ramana et al., 2013). So far, the optimum number of staff in the control room for single and multi-module SMR facilities and the number of control rooms necessary for the entire plant are unclear (Ramana et al., 2013; Hidayatullah et al., 2015). The regulators must review the number of staff proposed by the developers to warrant the safe operation of the plant (NEA OECD, 2016; SMR Regulators Forum, 2021). A goal-setting approach can assist in dealing with such uncertainties.

There is a consensus among several research papers and institutional reports (Kuznetsov, 2008; NEA OECD, 2016; SMR Regulators Forum, 2018; Carless et al., 2019; IAEA, 2021b; de la Rosa Blul, 2021; IAEA, 2022d) that the proposed way forward is the adoption of goal-setting approach instead of generic approaches to be in line with the SMR features, design provisions, the outcomes of the hazard and dose assessment and policy factors. In 2019, the United States enacted the Nuclear Energy Innovation and Modernization Act (NEIMA). Its purpose is to direct the US NRC towards a goal-setting approach, paving the way to licensing advanced reactor designs. (NEA OECD, 2021a).

Based on the above literature, the authors classify the prescriptive approach as a licensing barrier for the countries that employ this approach solely. The shift to a goal-setting approach involves the introduction of new acts, which is intricate and time-consuming. The legislators, nuclear regulatory authority and various ministries must be involved in bringing it to realisation. It is essential to overcome such barriers to preserve the innovative features of the SMR, which in turn, enhance the reactors' economic viability and the nuclear industry's performance (NEA OECD, 2020). Due to the prescriptiveness of specific regulations and the absence of policies, the SMR developers have to apply for exemption requests, which take time to be reviewed and granted.

3.3. Novelty in the technology

The nuclear industry is now emerging with a broad range of advanced small modular nuclear reactor technologies. They differ technologically from traditional reactors, and subsequently, the regulators are unaccustomed to them (NEA OECD, 2019; NEA OECD, 2021b; World Nuclear Association, 2021a; NEA OECD, 2022a). Sainati et al. (2015) pointed out that the uniqueness of the technology, the difference in its safety principles vis-à-vis conventional LRs and the absence of a well-defined and explicit regulatory framework for the SMR technology are factors that will increase the timeline of the licensing approval. These findings also agree with the conclusions from Ramana et al. (2013). They highlighted the understudy of the SMR's unique characteristics from a regulatory perspective and the absence of regulatory provisions to deal with the innovation.

A safety case contains information, analyses and justifications that the proposed designs are in compliance with the licensing requirements (IAEA, 2022d). The lack of relevant codes and standards due to these innovations makes it challenging and lengthy for the SMR proponents to demonstrate their safety cases and gain regulatory approval (NEA OECD, 2016; IAEA, 2017; SMR Regulators Forum, 2018; Budnitz et al., 2018; NEA OECD, 2020; NEA OECD, 2021b; IAEA, 2021b; IAEA, 2022d). The existing nuclear codes and standards would need to be updated, notably for SMR designs which significantly differ from the conventional large LWR NPPs. In certain cases, new codes and standards may need to be developed as necessary to address novel features of SMR designs (Liu et al., 2023). The lead time to prepare, review and approve those formal documents is substantial (Hidayatullah et al., 2015; Zinkle et al., 2016). Similarly, the regulators would require more time to analyse and validate those design and safety innovations before giving the licensing approval (Laina and Subki, 2012; Ramana et al., 2013; Cooper, 2014; Oh et al., 2014; Aydogan et al., 2015; Zinkle et al., 2016; Magwood and Paillere, 2018; Hussein, 2020).

A report by the World Nuclear Association (2021b) outlined that advanced nuclear reactor designs contain innovative features which may not be fully compatible with the existing human factors and ergonomics. According to Ramana et al. (2013) and Hidayatullah et al. (2015), the multi-modular features of the SMR add further responsibility to the plant operators. It is indispensable to ensure that the responsibilities bestowed upon the operators are manageable and do not affect their performance (Hidayatullah et al., 2015). In the event of an accident in one of the modules, the main regulatory concern is how it could impact the management of the other modules and the availability of resources that have to be shared between the multiple modules (SMR Regulators Forum, 2021; IAEA, 2022c; IAEA, 2022d).

The authors classify the novelty in the technology design as a licensing barrier because it is closely linked to the two previously discussed topic areas, which are, developing new or amending the existing legal and regulatory framework (Section 3.1.) and shifting from a prescriptive to a goal-setting approach (Section 3.2.). The timeline to make those changes is extensive, and several organisations must be involved in delivering that solution. Moreover, considering the widespread novelty of the technology, it will take a significant amount of time to acquaint with these features. The SMR technologies must demonstrate sufficient evidence to satisfy safety performance goals through safety cases simulating different limiting events (World Nuclear Association, 2015a; IAEA, 2017; IAEA, 2018b; NEA OECD, 2020). Limited operational data is available for the novel designs (Black et al., 2023). Sometimes, a demonstration project might be required to develop such evidence and assist the regulators in appreciating the uncertainties involved (SMR Regulators Forum, 2018), which would further stretch the deployment timeline.

3.4. Regulatory fragmentation

All nuclearised countries establish their nuclear safety requirements through specific national regulatory codes and standards (World Nuclear Association, 2015a; NEA OECD, 2020; NEA OECD, 2021b; World Nuclear Association, 2021b). Subsequently, a harmonised nuclear regulatory framework is absent across the globe, which is a considerable impediment to the deployment of SMRs (Ramana et al., 2013; Iyer et al., 2014; Sainati et al., 2015). The SMR designs should be licensable not only in their home country, but also in other countries to break into the global market, mitigate the risk of market saturation and enable standardisation of the designs (Ramana et al., 2013; Iyer et al., 2014; Hidayatullah et al., 2015; Schaffrath et al., 2021). Several studies suggest that a harmonised regulatory approach would favour deploying SMRs in the overseas market (Söderholm et al., 2014; Hidayatullah et al., 2015; Sainati et al., 2015; Playbell, 2017; Schaffrath et al., 2021; Nian et al., 2022).

However, regulatory harmonisation is highly complex and time-consuming (Hidayatullah et al., 2015; Sainati et al., 2015; World Nuclear Association, 2015a; SMR Regulators Forum, 2018). The main roadblock to converging towards a harmonised regulatory system is the strong willingness of the nuclearised countries to protect their regulatory independence and the national sovereignty of their regulatory practice (NEA OECD, 2020; NEA OECD, 2021b; World Nuclear Association, 2021a; World Nuclear Association, 2021b). Consequently, there is a significant reluctance to adapt their regulations to accommodate specific reactor design requirements from another country. The differences between the national regulatory frameworks are most likely to exist (SMR Regulators Forum, 2018; NEA OECD, 2021b; Liu et al., 2023). In addition, each country has varying environmental challenges; their environmental regulations can influence the reactor design (World Nuclear Association, 2020).

Due to regulatory fragmentation, the reactor designs need to undergo design changes in order to be accepted in the deployed country (World Nuclear Association, 2008; World Nuclear Association, 2015b; IAEA, 2018a; Thomas, 2019; NEA OECD, 2020; World Nuclear Association, 2020; World Nuclear Association, 2021b). Moreover, each country's solution to the problem might differ (Lloyd et al., 2021). There is inconsistency, uncertainty and significant variability in the regulatory review among the different regulatory bodies (Oh et al., 2014; Playbell, 2017; Budnitz et al., 2018; Zeliang et al., 2020). There is a subsequent increase in work for both the vendors and the regulators, leading to a more extended schedule and higher costs for the licensing activities (NEA OECD, 2020; World Nuclear Association, 2020; World Nuclear Association, 2021b). The NEA OECD (2020) estimated the adaptation costs due to regulatory fragmentation between countries to be around 30% of a common NPP's engineering, procurement and construction (EPC) costs.

The authors identify regulatory fragmentation as a barrier to licensing standardised SMRs across different countries. The shift to a harmonised regulatory framework requires the cooperation of regulatory bodies on an international scale with an attempt to harmonise their licensing and design certification (Hidayatullah et al., 2015; Liu et al., 2023). Such a significant undertaking is time-consuming. There is a gradual shift from the in-silo working mentality to having a small group of countries collaborating internationally. This approach enables like-minded nuclear regulators to share their knowledge, experiences, best practices, and lessons learnt while maintaining regulatory sovereignty and independence (NEA OECD, 2022a). For example, the US NRC and the Canadian Nuclear Safety Commission (CNSC) are supporting each other in reviewing advanced reactor technologies through a memorandum of cooperation (World Nuclear Association, 2020, 2021a).

3.5. Absence of in-factory certification

Contrary to large stick-built NPPs, SMRs are made of factory-produced modules. These individual modules are assembled in the factory to form integral assemblies. They are then transported to the sites, where they are assembled as a complete unit for operation (Mignacca and Locatelli, 2020b). There is an increase in the scale of modularisation and serial manufacturing. The establishment of an in-factory certification process can facilitate the licensing process of SMRs (World Nuclear Association, 2015a). It should provide a regulatory mechanism to inspect and certify the factory-fabricated integral assemblies in the manufacturing environment and promote efficiency in manufacturing (Sainati et al., 2015; IAEA, 2022c). There is a need to adapt the existing or develop a new licensing and regulatory approach as the transition towards modularisation takes place and to make provision for the in-factory certification process for the SMR integral assemblies (NEA OECD, 2016; IAEA, 2022d). The regulators should ensure adequate oversight of the manufacturing and testing process and implement essential quality assurance and quality control activities (IAEA, 2018b; SMR Regulators Forum, 2021; IAEA, 2022c). Such actions are essential to avoid incorrect manufacturing methods, materials and quality control approaches and meet requirements. Other emerging issues are the traceability of the modular components when manufactured using a diversified supply chain and the involvement of more than one regulator alongside their licensing process (Sainati et al., 2015; NEA OECD, 2016; NEA OECD, 2021b). The imported components of a SMR, even if factory certified in another country, are still contingent on the licensing requirements of the country where they will be assembled and operated (Lloyd et al., 2021).

The authors categorise the absence of an in-factory certification process as a barrier to the licensing of SMRs. The establishment of such a process is linked to the adaption of existing or development of a new regulatory framework (Section 3.1.) and the element of harmonisation of requirements (Section 3.4) so that the components of the SMR can be standardised and deployed on the global market. As previously discussed, the intricacy involved in making these shifts results in a longer timeframe of more than a decade. In addition to the legislators, significant cooperation between the regulatory body and the SMR manufacturer is necessary. There is added complexity if regulators and manufacturers from different countries are involved.

4. Licensing challenges

4.1. Fees charged by regulators

The fees charged by the regulators come from two primary sources, annual regulatory fees charged to the operators of the NPPs in operation and the licensing fees charged to the applicants. The cost of licensing a FOAK SMR is steep because it requires a lengthy and resource-intensive licensing process (Mignacca et al., 2020). Moreover, such cost is independent of the reactor's power output. As a consequence of this diseconomy of scale, it is detrimental to the economics of SMRs as compared to LRs (Locatelli et al., 2014; Cooper, 2014). Concerning the annual regulatory fees, Vegel and Quinn (2017) reported that if the same regulatory fee is applied to a 45MWe SMR and LRs over 2000MWe capacity, the licensing cost per kW for the SMR is more than 20 times higher as compared to the LRs because of the reduced output.

The authors classify the fees charged by the regulators as a licensing challenge. The nuclear regulatory authority, a single organisation, is responsible for reviewing its existing regulatory fee model. For instance, in 2016, the US NRC had to revise their annual fee methodology to ensure that the deployment of SMRs is not impeded by an unfair and inequitable payment of the annual fees (US NRC, 2015). Such changes can be effected in the short or medium term to address the discrepancies in the present policy and to ensure that they do not obstruct the deployment of innovative technologies (Vegel and Quinn, 2017). In the US NRC case, it took them seven years (US NRC, 2015). Moreover, as the regulators move along the learning curve of licensing FOAK SMR to Nth-of-a-kind (NOAK) SMR, the licensing process will not be as resource intensive and lengthy as the first one.

4.2. Regulatory capability gaps

Over the past decades, regulatory bodies have mainly been exposed to light-water reactors. There has been a significant gap where no NPPs were constructed in Europe, causing an erosion in the capabilities of the nuclear industry (NEA OECD, 2020; NEA OECD, 2021b). An article from the Nuclear Law Bulletin advanced that the NRC's current regulations have been mainly designed and applied to LWR technologies and that the regulatory authority does not have the necessary regulatory process to review and license non-LWR technologies (NEA OECD, 2017). Ramana et al. (2013) and Mignacca et al. (2020) also emphasised the limited experience and capability in licensing FOAK SMR. As such, it is plausible that the regulators will encounter several hurdles during the regulatory review process, given the variety of novel technologies and that they will have to go through a steep learning curve (World Nuclear Association, 2021a; Black et al., 2023).

This research has identified the capability gap as a challenge as it refers to a single organisation, the regulatory authority, and it can be resolved within ten years with the appropriate support. They should be provided with the necessary training programs to develop their regulatory knowledge, be efficient with the licensing process, and reduce the regulatory gap between existing regulations and the ones necessary for deploying advanced technologies (NEA OECD, 2019; SMR Regulators Forum, 2021; Nian et al., 2022). They should collaborate closely on an international level with regulators from other countries. Such measures will ensure that the regulators do not slow down the adoption of these technologies and that they are kept abreast of recent developments. It will also positively influence the public's perception of the regulator's capability and the maturity of their regulatory process (NEA OECD, 2022a). For example, in the United Kingdom, around £12 million was invested in its regulatory authorities, the Office for Nuclear Regulation (ONR) and Environment Agency (EA), to deal with this challenge (IAEA, 2021b).

4.3. Lengthy licensing duration

During the regulatory and licensing reviews, the public is consulted as part of the regulatory process in numerous countries. Without their go-ahead, the project cannot go forward. The public hearing can substantially affect the project timeline. For example, in France, there is National Public Debate Commission in addition to the normal public hearing; Canada and Switzerland involve significant public involvement compared to others (Bredimas and Nuttall, 2008). In the case of LRs, the public hearing takes around one year (Ramana et al., 2013). The same timeline can be unfavourable for SMRs as they are expected to be licensed and deployed quicker than LRs. The lack of strong collaboration between the licensing regulators and reactor developers, for example, on the SMR KAERI project in South Korea, is another reason for the lengthy licensing process (Ramana et al., 2013).

Furthermore, the higher the level of design maturity and completeness of a FOAK SMR at the early stage of the project, the lower the risk of encountering licensing delays and cost overruns during the pre-licensing and licensing stages (World Nuclear Association, 2021a). However, such regulatory expectation is a challenge to developers who require an incremental approach to validate their technical design and to obtain project funding (NEA OECD, 2017). There is also the challenge of proprietary information whereby the SMR designers can share only a limited amount of information at the initial stages of the project (SMR Regulators Forum, 2018). The latter cannot share potential solutions to some of the queries raised by the regulators, which increases the risks of delays in the licensing process (IAEA, 2017).

The authors recognise the lengthy licensing duration as a challenge to licensing SMRs. A single organisation, the applicant, deals with the regulators during the licensing process. These identified issues during the licensing process can be resolved within a decade. The public hearing (Sainati et al., 2015), compliance with non-nuclear permits (World Nuclear Association, 2015b), and sensitivity of proprietary information (SMR Regulators Forum, 2018) are most likely to exist. Building an agreed timetable between regulators and applicants around these factors is essential. Conversely, the pre-licensing step encourages early engagement between the applicant and the nuclear regulators to proactively discuss the difficulties encountered during the regulatory and licensing review (World Nuclear Association, 2021a; NEA OECD, 2022a). It thus reduces the risk of delay. Additionally, early engagement with the local communities can clarify their concerns regarding the innovative technologies and educate them about their potential benefits (IAEA, 2021b; NEA OECD, 2021b). It can subsequently help alleviate the challenge of a lengthy public hearing process.

5. Conclusion

There is a cornucopia of literature on the subject of SMRs. However, regarding the licensing of SMRs, the literature is limited and often fragmented among other discussions. Through a systematic literature review, the authors have identified six licensing barriers and three licensing challenges from peer-reviewed academic papers and institutional reports from the IAEA, WNA and NEA-OECD organisations, as shown in Table 4. The identified licensing barriers require a lengthy timeline (more than ten years) to be broken down, and multiple organisations are involved in delivering the solution. The identified licensing challenges can be dealt with within ten years, and a single organisation is involved in delivering the solution.

This paper feeds into the ongoing discussions on SMRs (Carelli et al., 2010; Locatelli et al., 2014; Hidayatullah et al., 2015; Testoni et al., 2021). It echoes the thoughts of the existing discussions on the licensing of SMRs (Ramana et al., 2013; Sainati et al., 2015). It further contributes by categorising the research findings into licensing barriers and challenges to show their relevance in deploying SMRs from a timeframe and ownership standpoint. Such categorisation informs the stakeholders, such as policymakers, nuclear regulators, the nuclear industry, legal experts, investors, the public and academics, on the issues that need prioritisation and that need to be tackled from the root cause.

Furthermore, the findings highlight the following implications for deploying SMRs. The high fees charged by regulators and the lengthy duration of the existing traditional licensing processes have a negative bearing on the economics of the SMR. In addition, the present legal and regulatory framework and the prescriptive regulatory approach overlook certain innovative features of the SMRs, further hindering economic viability. Subsequent to these issues and the gap in regulatory capability, the novelty in the technology requires more time to be reviewed and validated, thus stretching the timeframe of the licensing process. Due to regulatory fragmentation, the SMR designs have to be adapted according to the regulatory requirements of the destination country, leading to additional scope, cost and time for both the SMR vendor and regulator. Additionally, the absence of an in-factory certification process could slow down the deployment of the mass-produced components from the factories. All of the above points cause an increase in the overall project cost and timeline, which is a constraint from an investor's perspective.

It is worth noting that the nuclear industry is undergoing changes to facilitate the implementation of SMRs. Early interactions are taking place among relevant stakeholders, regulatory bodies of different countries are working closely together, and there is a move towards adopting a goal-setting regulatory approach. However, there is still more work to be done.

Table 4
Identified licensing barriers and licensing challenges.

Licensing Barriers	Licensing Challenges
(1) Existing legal and regulatory framework	(1) Fees charged by regulators
(2) Prescriptive regulatory approach	(2) Regulatory capability gaps
(3) Novelty in the technology	(3) Lengthy licensing duration
(4) Regulatory fragmentation	
(5) Absence of in-factory certification	

The deployment of SMRs from a licensing perspective requires adapting the existing legal and regulatory framework, shifting from a prescriptive approach, appreciating the technological novelty, harmonising the regulatory framework, and creating an in-factory certification process. Adjusting the fees charged by regulations, enhancing the capability of the regulators, and reducing the licensing duration are all equally essential. There is a need for policy developments to support the above points raised to create the proper infrastructure for the licensing of SMRs. From a practice perspective, dealing with those issues without compromising the safety requirements will enhance the economics of SMRs and make them attractive to potential investors. In the bigger picture, deploying SMRs will enable nuclear energy to play a critical role in combatting climate change and energy security.

As a limitation, the article primarily employs a project management perspective to discuss the major licensing barriers and challenges that impact the global deployment of SMRs. However, additional barriers and challenges may impede the successful implementation of SMRs beyond those discussed in academic papers and institutional reports. To provide a comprehensive understanding of the SMR deployment situation, viewpoints from other relevant expertise areas alongside the project management perspective can be beneficial. These inputs can provide additional insights on various aspects of SMR licensing, such as the importance of having complete final designs for safety considerations, the scaling challenges in SMRs, the development of expertise among scientists and technologists involved with the novel designs, and the need for financial resources.

Moreover, the authors believe that the subject of licensing SMRs merits further research in the following avenues: (1) explore the implications of in-factory certification in licensing SMRs; (2) investigate the practicalities of early-joint regulatory review process between like-minded regulators on regulatory harmonisation; (3) develop an improved understanding of the influence of the licensing challenges and barriers on the economics of SMRs; and, (4) explore the role of nuclear law in the licensing and deployment of SMRs.

CRediT author statement

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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.

Data availability

Data will be made available on request.

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Appendix A. Synonyms of keywords for Scopus search

Small Modular Reactor: SMR, Small Modular Reactor*, Small Modular Nuclear Reactor*, Small Medium Reactor*, Advanced Modular Reactor*, Gen* IV reactor*

Nuclear

Licensing: Licen*, Permit*, Authorisation, Regulat*, Law*, Legal*, Legislations, Statutes, Treat*, Conventions, Standards, Prescriptive based, Performance-based, Goal Setting, Emergency Planning Zone, EPZ, Safe*, Security, Defence-in-Depth, DiD, Graded Approach.

Barrier and Challenge: Challeng*, Barrier*, Obst*, Constrain*, Complica*, Difficult*, Issue*, Impediment*, Problem*, Novel*, Limit*

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