Energy 206 (2020) 118137

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Deeds not words: Barriers and remedies for Small Modular nuclear Reactors

Benito Mignacca, Giorgio Locatelli*, Tristano Sainati

School of Civil Engineering, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

ARTICLE INFO

Article history:
Received 11 March 2020
Received in revised form
26 May 2020
Accepted 13 June 2020
Available online 20 June 2020

Keywords:
Nuclear power
Small modular reactors
Modularisation
Circular economy
Licensing
Decommissioning

ABSTRACT

There is a growing interest in Small Modular nuclear Reactors (SMRs) driven mostly by the concerns in decarbonising the electricity and heat sectors. Despite the expected advantages of SMRs with respect to large reactors (e.g. construction schedule reduction, lower upfront investment per unit) and at least two decades of studies, investments in SMRs have been extremely limited. Leveraging a literature review, in-depth discussions, and a questionnaire survey, this paper aims to identify and rank general elements hindering SMR construction, specific licensing and regulatory elements affecting SMR construction, and elements favouring or hindering the reuse of SMR modules. The results show that financial and economic issues (including perceived investment risk, availability of cheaper technologies to generate electricity) are the main barriers for SMR construction. Government support for financing the first-of-a-kind and developing a supply chain could allow overcoming these barriers. Time, cost and risk of the licensing process are critical elements for SMR construction; therefore, policies should be in place to support stakeholders. The economic feasibility can hinder the opportunity of reusing SMR modules. Design and interface standardisation are the main enabling factors of reusing SMR modules. Further studies on SMR decommissioning through a "circular economy" lens are needed.

1. Introduction

Affordable and clean energy is one of the 17 United Nations sustainable development goals [1]. Nowadays, around 85% of the world global energy consumption is met by fossil-based fuels [2,3]. However, some of the fossil's fuels reserves could run out in this century [4,5], and the consumption of coal, natural gas and oil for electricity and heat is one the greatest sources of global greenhouse gas emissions [6]. Along with the improvement in energy efficiency and the deployment of technologies using renewable plants, Nuclear Power Plants (NPPs) are one of the key technologies to decrease greenhouse gasses in generating electricity [7]. However, NPPs require a multi-billions upfront investment, five to ten years of construction and are often delivered over budget and late [8]. Environmental goals, along with the hurdles in building Large Reactors (LRs), are key reasons behind the growing interest of academics, practitioners and governments towards Small Modular nuclear Reactors (SMRs).

SMRs are "*newer generation [nuclear] reactors designed to generate electric power up to* 300 MW, *whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises*" [9] (Page 1).

Globally, there are about 50 SMR designs at different stages of development [10]. SMR designs adopt both mature technologies such as light water reactor (the technology used by the vast majority of NPPs in operation), less mature technologies such as sodium-cooled reactor, and "never commercially operated" technologies such as molten salt fuelled (and cooled) advanced reactor [9].

Discussions about technical and economic aspects of SMRs started to gain traction in the early 2000s (e.g. see the IRIS reactor [11]). However, as 2020 there are only two floating SMRs in operation [Akademik Lomonosov 1 and 2 (35 MW each) in Russia]. Furthermore, there are only two nuclear reactors below 300 MW under construction [Carem25 (29 MW) in Argentina and Shidao Bay-1 (210 MW) in China] out of 53 [12]. The reasons behind the slow adoption of SMRs are unclear and investigated in this paper. This paper addresses three research questions leading to three main contributions, relevant for the stakeholders involved in the SMRs business (e.g. policymakers, vendors, regulators) enabling to

* Corresponding author.
E-mail addresses: cnbm@leeds.ac.uk (B. Mignacca), g.locatelli@leeds.ac.uk (G. Locatelli), T.Sainati@leeds.ac.uk (T. Sainati).

https://doi.org/10.1016/j.energy.2020.118137

focus on a series of steps to promote the construction of SMRs and improve SMR life-cycle, including decommissioning.

The first contribution relates to general elements hindering SMR construction addressing the following research question (RQ):

RQ1: What are the most important general elements hindering the construction of SMRs?

The second contribution relates to a specific critical issue for SMR construction, i.e. SMR licensing and regulation [13] addressing the following RQ:

RQ2: What are the main licensing and regulatory elements hindering or favouring the construction of SMRs?

The third contribution relates to SMR decommissioning, i.e. the opportunity to reuse SMR modules. Modularisation, in addition to being a major determinant of the expected construction schedule reduction of SMRs with respect to LRs [14], could enable opportunities for improving SMR decommissioning. A novel topic potentially improving SMR decommissioning is the link between modularisation and circular economy (CE), i.e. "Modular CE" [15,16]. [15] define Modular CE as: "*the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials*". According to Ref. [15], modules of energy infrastructure (SMR modules in this case) could be designed in a way that when the infrastructure reaches the end of life, modules that have still useful life could be reused in other infrastructure. In this regard, this paper addresses the following RQ:

RQ3: What are the main elements hindering or favouring the reuse of SMR modules?

The rest of the paper is structured as follows. Section 2 details the methodology; Section 3 presents the three areas investigated in this paper: General elements hindering SMR construction (3.1), SMR licensing and regulation (3.2), and SMR decommissioning (3.3); Section 4 presents and discusses the results; section 5 concludes the paper.

2. Research design

The research design of this paper is based on a critical analysis of the literature, in-depth discussions with experts in SMRs, modularisation and CE, and the data collected via a questionnaire survey distributed to SMR experts. The research has been conducted following the methodology used by Ref. [17,18], and consisting of three main steps as detailed in the next paragraphs.

Step 1: Derivation of the elements constituting the survey through a critical analysis of the literature and in-depth discussions with experts in SMRs, modularisation and CE.

This step, lengthy discussed in Section 3, led to five tables (Tables 1–5) summarising: 1) General elements hindering SMR construction, 2) Licensing and regulatory elements hindering SMR construction, 3) Licensing and regulatory elements favouring SMR construction, 4) Elements hindering the reuse of SMR modules, and 5) Elements favouring the reuse of SMR modules.

Step 2: Collection of primary data through a questionnaire survey sent to NPP experts via SurveyMonkey.

The questionnaire survey had four sections. The first section was designed to collect information about NPP experts:

1. The main area of expertise;
2. Years of experience in the nuclear sector;
3. Familiarity with SMRs (1 = not familiar, 2 = slightly familiar, 3 = moderately familiar, 4 = familiar, 5 = very familiar);
4. The most familiar country with the deployment of SMRs.

In the second, third and fourth section, the five tables derived from Step 1 were provided. For each element in the tables, the experts had to provide a score through a 5 point Likert scale (1 = not important, 2 = slightly important, 3 = moderately important, 4 = important, 5 = very important). Experts were given the opportunity to add other elements or to comment about the questions, and not to score elements where they were unsure.

Fig. 1 shows the structure of the questionnaire survey.

Before sending the questionnaire to the entire sample, several measures were adopted to improve the reliability of the data collected. According to Ref. [19], the main goal of improving reliability is "*to decrease the possibility that the measure is due to misunderstanding, error, or mistake, but instead reveals the true score*". The authors initially tested the questionnaire survey with ten experts in the nuclear sector (with different expertise and seniority) asking them to comment about the clarity of the questions and the possibility to add or eliminate elements. The authors improved the questionnaire following their recommendations. In order to ensure consistency, their responses were not considered in the data analysis (Section 4).

The questionnaire survey was then conducted from the 22nd of November 2019 to the 20th of January 2020 and distributed to 2174 professionals in the nuclear sector, granting anonymity. In order to improve the response rate, a personalised email linking to the questionnaire was sent. Out of 2174 questionnaires sent out, 151 were returned with valid responses (response rate of 7%). Out of 151 valid responses, 97 are familiar (43) or very familiar (54) with SMRs. These 97 responses are considered for this paper. The Appendix provides the details of the data collected.

Step 3: Data analysis.

Based on similar previous studies, such as [17,20], the mean score method was used to determine the ranking in descending order of the elements in Tables 1–5, as perceived by the 97 experts.

Cronbach's coefficient alpha was calculated using IBM SPSS Statistics 26 to measure internal consistency among the elements to evaluate the reliability of the five-point scale. [21] recommends a value of 0.7 or higher. Considering each section of the questionnaire survey focuses on a different area, Cronbach's coefficient alpha was calculated for each section (i.e. general elements hindering SMR construction, elements of licensing and regulation hindering SMR construction, etc.) and resulted higher than 0.7 for all the sections.

Results of the data analysis are in-length discussed in Section 4.

3. Background and derivation of the questionnaire survey

Enhanced modularisation and modularity are the main characteristics which differentiate SMR construction from traditional monolithic LRs.

Modularisation (factory fabrication, transportation and installation on-site of modules [22]) can increase the quality of the components, reduce the construction schedule and maintenance costs leading to a cost-saving in labour and construction [23–25]. The positive (or negative) impact of modularisation on the capital cost strongly depends on the extent of its application [24,26–28]. Several challenges are associated with modularisation. For instance, the supply chain start-up costs are higher for a modular plant than stick-built [29], along with more complicated project management and logistics [14,25,30].

Modularity (a plant built by the assembly of identical or nearly identical reactors of smaller capacity [22]) translates into four main advantages for SMRs with respect to LRs: 1) Incremental capacity addition, allowing to generate revenue from the first SMR to potentially co-finance the construction of further units [31]; 2) Co-siting economies (several units on the same site), allowing to save on fix and semi-fix costs (e.g. licences, human resources) when installing the subsequent units [23,32], and to share personnel, upgrades (e.g. software) and spare parts across multiple units; 3)

Stronger and faster learning considering that more SMRs than LRs are built for the same power installed, allowing to reduce investment cost [31,33]; 4) The opportunity of switching some of the SMRs for cogeneration, allowing to run at the full nominal power and maximum conversion efficiency [34,35].

Fig. 2 illustrates the different classification of NPPs according to the construction strategy.

Next sections introduce the three areas investigated in this paper (i.e. General elements hindering SMR construction (3.1), SMR licensing and regulation (3.2), and SMR decommissioning (3.3)), explaining the gap in knowledge and deriving the list of the elements constituting the questionnaire survey.

3.1. General elements hindering SMR construction

There is a long-standing interest in SMRs because of the aforementioned unique characteristics, but a paucity of investment in construction, and it is unclear what is slowing SMR adoption. This paper aims to fill this gap in knowledge, identifying and ranking general elements hindering SMR construction.

Table 1 presents a list of elements potentially hindering the construction of SMRs that emerged from the literature review and in-depth discussions.

Table 1 shows that the elements potentially hindering SMR construction are across all the main phases of SMR life-cycle (design, construction, operation and decommissioning) and are related to four main categories:

- Economics of construction. SMR smaller size with respect to LRs determines the "diseconomies of scale" [40–42] and could make unattractive the investment in SMRs [39,40]. Furthermore, there is still uncertainty about the O&M and decommissioning costs of SMRs. Most of the literature focuses on analysis at plant-level (1 SMR vs 1 LR) or site-level (X SMRs vs 1 LR of equivalent total size) [16], almost ignoring that the focus at the programme level can be a major determinant [8], as in the case of the "successful nuclear programme" in South Korea [47].
- Economics of operations. Availability of cheaper and/or less capital intensive alternative technologies to generate electricity and the wholesale price of electricity emerged as two potential elements hindering SMR construction [40]. In this regard, the O&M costs are also a key parameter, considering that several reactors in the USA have been closed because the electricity price was so low that did not even cover the operating and upgrading costs [48].
- Financing. The investment cost of a single SMR can be a fraction than a single LR. However, considering the same total power to be installed overall, the total cost of a programme might be similar [49], ranging in the decades of billions of dollars [16]. NPPs are often delivered over budget and late [8], determining a high perceived investment risk by investors.
- Readiness. The lack of a first-of-a-kind (FOAK) or "reference plant" is a critical issue for almost all SMRs, while non-light water reactors also need substantial research and development. Furthermore, a consistent up-front investment is needed to develop the supply chain [16]. There is an incompatibility with SMR characteristics (e.g. shorter construction schedule) of the current licensing processes developed for LRs. For these reasons, investors perceive a relevant completion risk, particularly for the FOAK SMR.

3.2. SMR licensing and regulation

All NPPs are subject to thorough regulatory oversights that are primarily concerned about the safe and secure use of nuclear power [50]. A key component of the regulatory scrutiny is the licensing process that is a stage-gate process taking place before, and along, the construction of NPPs. The regulatory body assesses the technical features of the reactor (plant), the capabilities of the operator (e.g. people, procedures, financial capabilities), the suitability of the nuclear site, and the interactions between these aspects [51,52]. The regulatory body has the authority to grant licenses for the construction and operation of NPPs. It can force the prospective operator (i.e. licensing applicant) to stop the construction, provide additional information and safety demonstration, re-design or rebuild part of the reactor [51,53,54]. These compelling actions can severely harm the construction performance of NPPs that are critical for their economic competitiveness. Historically, each country developed its own licensing processes, implicitly having in mind large stick-built NPPs. Consequently, the deployment of SMRs sees peculiar challenges from a licensing point of view.

Firstly, the actual timing of traditional licensing processes in many countries is compatible with LRs but can delay the faster deployment of SMRs, reducing their financial advantages [55].

Secondly, the cost of licensing for the FOAK is almost independent of the size; therefore, the cost per kW is higher for SMRs with respect to LRs because of their reduced power output [29].

Thirdly, to realise the economic benefits envisaged by SMRs, significant changes to the traditional licensing process are required,

Table 1
General elements hindering SMR construction. Layout adapted from [17].

General elements hindering SMR construction	Main sources
- Availability of funds	[16,36–41]; In-depth discussions
- Lack of experience in operations	
- Perceived investment risk	
- Political support	
- Site availability	
- Technology readiness	
- Uncertainties about the end of life	
- Diseconomies of scale with respect to LRs	[40–42]
- Lack of planning at programme/country level	[16,43,44]
- Uncertainties about the O&M costs	
- Uncertainty about the cost/benefit analysis	
- Lack of reference plant(s) (or lack of FOAK unit)	[16]; In-depth discussions
- Supply chain availability	
- Licensing and regulatory constraints	[13,29,45]; In-depth discussions
- Public acceptability	[36,46]
- Availability of cheaper alternative technologies to generate electricity	In-depth discussions
- The wholesale price of electricity	

Table 2
Licensing and regulatory elements hindering SMR construction. Layout adapted from [17].

Licensing and regulatory elements hindering SMR construction	Main sources
- Absence of in-factory certification - Exclusive liability of the nuclear operator - Inability to separate the license for design, site and the operator - The limited experience and capabilities of the regulatory body - The sequence of steps characterising the licensing process - Timing of the licensing process - Size of the EPZ	[13,56]; In-depth discussions
- Availability of slots for the licensing (resource availability in the regulatory body to review the design) - Risks involved in the licensing process	In-depth discussions
- Ownership and financial requirements associated with the operator of a nuclear power plant	[55]; In-depth discussions
- Cost of the licensing process	[29]

Table 3
Licensing and regulatory elements favouring SMR construction. Layout adapted from Ref. [17].

Licensing and regulatory elements favouring SMR construction	Main sources
- Allow the in-factory certification - Change the key steps of the licensing process - Enhance the liability of technology vendor and supplier - Reduce the time of the phases of the licensing process in parallel with the construction and commissioning of SMRs - Reduce the size of the EPZ	[13,56]; In-depth discussions
- Create an entirely new regulatory framework for SMRs - Promote the early meetings with the regulatory body in order to reduce the licensing and regulatory risk - Reduce the cost of the licensing process before construction - Reduce the time of the licensing process before construction	[52,57]; In-depth discussions

in particular concerning the scope and type of regulatory assessments. Some SMRs are based on integral designs that are "assembled and sealed" in factories as opposed to nuclear sites [31,46]. This technical feature is pivotal for the modularisation and involves critical drawbacks for traditional licensing processes. Additional regulatory assessments (e.g. inspections, tests) are required at factories, potentially in third countries, implying changes in established procedures of regulatory bodies. Another concern is whether certifications released at the factory are still valid after the transportation and installation at the site. In traditional licensing processes, the burden of proof is on the applicant, early certifications (and authorisations and license) do not prevent regulatory bodies to either reject operating license or impose the compelling actions previously described. As a result, the perception of completion risk from a nuclear operator is relevant until the final operating license is granted. Some of the envisaged advantages of SMRs concerning the installation efficiency and risk reduction can clash with the intrinsic features of traditional licensing processes.

Finally, promoters of SMRs advocates for reducing the regulatory requirements for SMRs, as these designs are inherently safer compared to LRs. For example, alternative siting requirements can be considered, including the reduction of the Emergency Planning Zone (EPZ) [56]. In many countries (e.g. France, USA) some of these requirements are introduced by statutes (e.g. nuclear law), and their amendment requires a parliamentary discussion, which is a lengthy process, particularly if the introduction of SMRs is not perceived as an urgent priority in the country. Therefore, the status quo of the existing legal and regulatory frameworks, as well as the procedures within regulatory bodies, is something difficult to change in the short term and might represent a critical impediment to the realisation of some envisaged advantages of SMRs.

The bottom line is that there is plenty of licensing and regulatory elements potentially affecting SMR construction. However, it is unclear which the key elements are, and which changes could lead to a step forward for SMR construction. This paper aims to fill this gap in knowledge, identifying and ranking licensing and regulatory elements affecting SMR construction.

Tables 2 and 3 respectively summarise the licensing and regulatory elements hindering and favouring the construction of SMRs emerged from the literature review and in-depth discussions.

3.3. SMR decommissioning: Linking modularisation and CE

NPP decommissioning projects are risky, complex, long, expensive and prone to overbudget [58,59]. As aforementioned in the introduction, SMR decommissioning could be improved harnessing the link between modularisation and CE. Regarding CE, there are a plethora of definitions, as reviewed by Refs. [60]. This paper is based on the definition of [61]: "*The basic idea of the CE is to shift from a system in which resources are extracted, turned into products and finally discarded towards one in which resources are maintained at their highest value possible*". [15] introduces the link between modularisation and CE in energy infrastructure, defining Modular CE as a strategy preserving the peculiarities of modularisation but also aiming to facilitate the reuse/repair/replacement/

Table 4
Elements hindering the reuse of SMR modules. Layout adapted from [17].

Elements hindering the reuse of SMR modules	Main sources
- Contamination (chemical, radioactive, etc.) - Difficulty in disassembly the modules - Lack of consideration in the original design - Lack of maintenance to maintain the integrity - Lack of successful track record - Public acceptance	In-depth discussions
- Difficulty in module transportation - Economic feasibility - Lack of design standardisation - Lack of standardisation of the interfaces - Licensing and regulatory constraints - Technology obsolescence	[15], In-depth discussions

Table 5
Elements favouring the reuse of SMR modules. Layout adapted from [17].

Elements favouring the reuse of SMR modules	Main sources
- A new licensing and regulatory framework - Political support - Standardisation of the design - Standardisation of the interfaces - The creation of a second-hand market	[15], In-depth discussions
- Continuous monitoring of module conditions - Cost to dispose of a potentially reusable module	In-depth discussions
- Original plant engineered with the "design for disassembly"	[15,16], In-depth discussions

recycling of modules/components/materials. The key insight of Modular CE strategy is to harness the advantages of modularisation to improve the sustainability of energy infrastructure. In other words, translating [15] in the specific case of SMRs, SMR modules (e.g. turbines) could be designed in such a way that when SMR plant reaches the end of life, modules that have still useful life could be reused in other SMR plants. This approach would allow exploiting the residual lifetime of certain SMR modules with longer life. Furthermore, modularisation facilitates the replacement and repair of modules and components, as well as the recycling of materials contributing to pursue two United Nations Sustainable Development Goals: Goal 7 (Affordable and Clean Energy), and Goal 9 (Industry, Innovation and Infrastructure) [62].

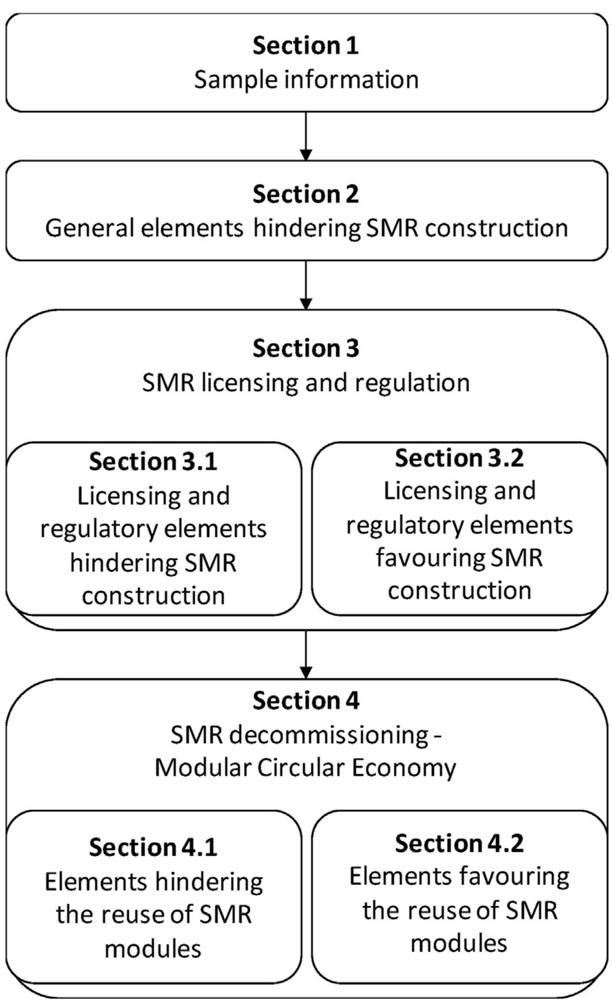

Fig. 1. Structure of the questionnaire survey.

However, the link between modularisation and circular economy in the case of SMRs is an under-researched area. [16] only mentions the opportunity to leverage modularisation to implement CE principles, and points out the "design for disassembly" as a key enabling factor. This paper, focusing on the opportunity of "reusing SMR modules" to improve SMR decommissioning, aims to identify and rank the elements affecting the reuse of SMR modules. Tables 4 and 5 summarise respectively the elements hindering and favouring the reuse of SMR modules emerged from the literature review and in-depth discussions.

The in-depth discussions confirmed most of the elements introduced by Ref. [15] in the general case of energy infrastructure. In addition, the experts suggested other elements that could hinder the reuse of modules in the specific case of SMRs, such as module contamination, lack of successful track record, public acceptance, etc. (all of them in the first section of Table 4). The elements affecting the reuse of SMR modules in Tables 4 and 5 are related to three main categories:

- Design. A key requirement for the reuse of SMR modules is the design and interface standardisation [15]. Modular CE strategy in general and the reuse of SMR modules in particular need to be considered in the early design stages, including requirements such as "design for disassembly" [15,16] and the continuous monitoring of module conditions.
- Economics and market: The reuse of SMR modules could add complexity both in terms of regulation and design phase in general, which could lead to an increase in cost and schedule. The economic feasibility could limit the implementation of the Modular CE strategy in general and the reuse of SMR modules in particular [15]. Political support could solve this potential barrier. The creation of a market for second-hand modules is one of the key enabling factors for the reuse of SMR modules [15].
- Peculiar SMR challenges: The contamination (chemical, radioactive, etc.) of SMR modules could limit the reuse. Furthermore, transportation is one of the challenges of modularisation [30], and its complexity could increase in the case of contaminated modules. A new licensing and regulatory framework dealing with the reuse of SMR modules could be needed.

4. Results and discussions

4.1. Sample information

The 97 experts have, on average, 32 years of experience in the nuclear sectors. The majority (89%) is familiar with the deployments of SMRs in the United States of America, and the remaining part in Canada (5.1%), no specific country (4.2), Japan (1%), and United Kingdom (1%). The majority of the experts (48.4%)

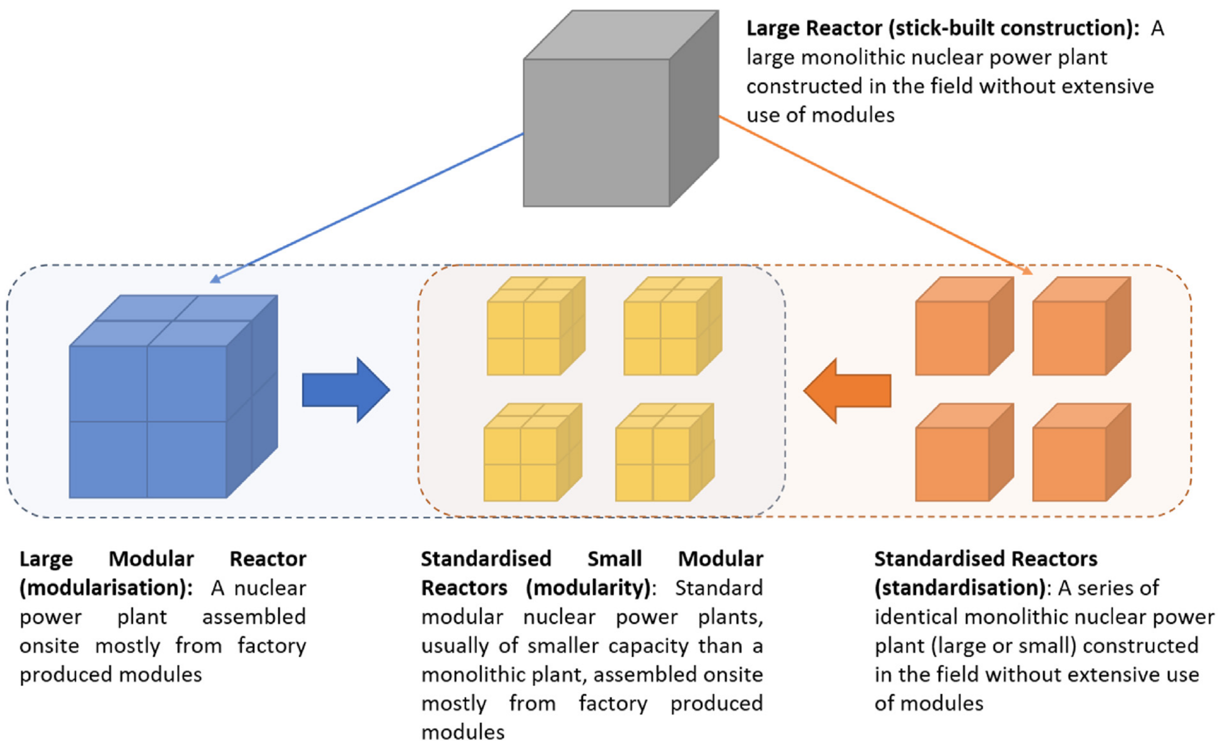

Fig. 2. Classification of NPPs. Adapted from [16].

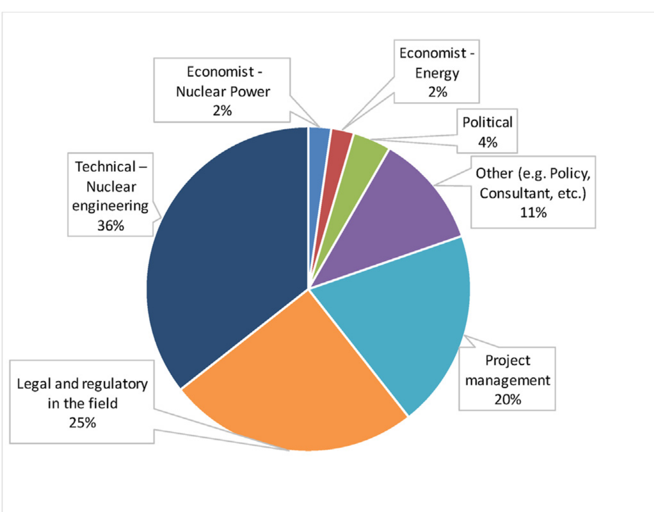

Fig. 3. Experts' areas of expertise.

highlighted "Technical — Nuclear Engineering" as one of their main areas of expertise (each expert could choose more than one area of expertise). Fig. 3 summarises the experts' areas of expertise.

4.2. General elements hindering SMR construction

4.2.1. Results

Fig. 4 shows the ranking of the general elements hindering the construction of SMRs in Table 1, as scored by the experts (see Appendix Afor more details about the frequency of the responses).

Consistently with [17], elements with a Mean Score (MS) higher than the average total value (3.46) can be defined as "critical general elements" strongly hindering the construction of SMRs. Therefore, from the 1st (perceived investment risk) to the 11th (supply chain availability) ranked element can be defined as "critical general elements" to SMR construction.

One of the experts commented directly about the 3rd-ranked element (i.e. the availability of cheaper alternative technologies to generate electricity) and indirectly about the 1st-ranked element (i.e. the perceived investment risk):

> *"The problem with new reactor deployment is almost all financial… the industry has not credibility that it can deliver for the projected cost and schedule, and other forms of electricity are much cheaper- cheap gas and subsidised renewables".*

Another expert commented about the need for political support (6th-ranked) to speed up the construction of SMRs:

> *"To achieve rapid development, government may have to fund first units".*

A third expert commented about the relationship between the safer design (and therefore the size of the EPZ) and the public acceptability:

> *"Emergency response support for local communities. Large nuclear plants pay fees/taxes to supplement local police and fire departments for emergency needs. The designs for SMRs suggest the risk is very low, and emergency planning zones don't extend beyond the site. This means no funds would be given to support local emergency responders, which may result in public opposition due to the appearance of understating potential risks, and significantly changing local expectations established by larger nuclear plant operations".*

One of the experts commented highlighting elements favouring

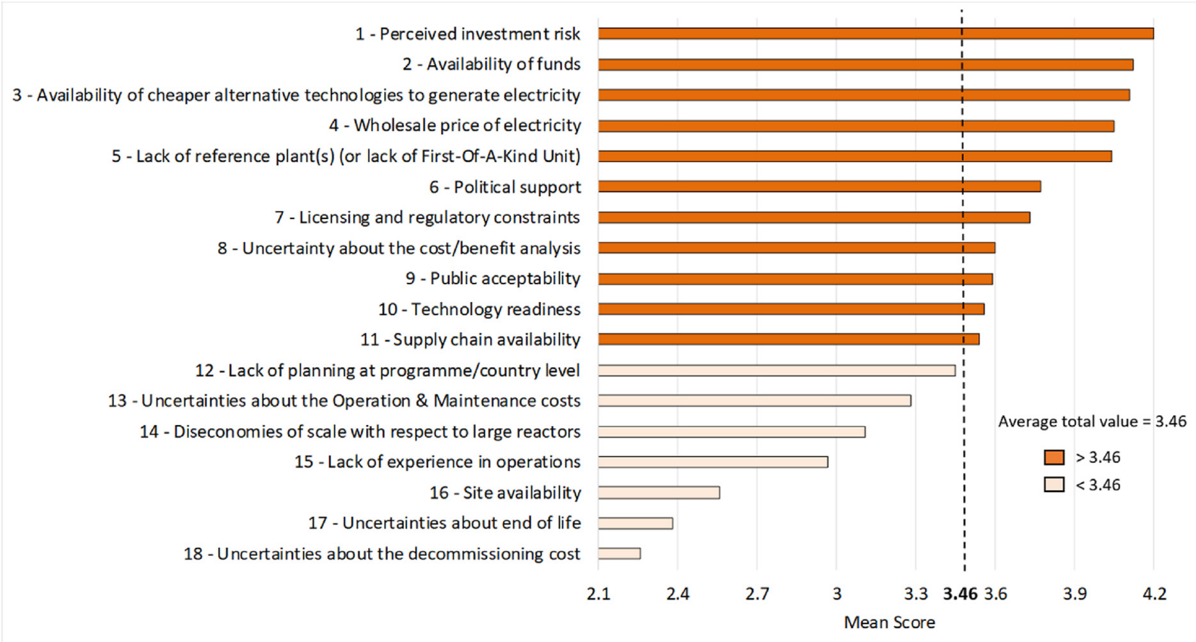

Fig. 4. Ranking of the general elements hindering SMR construction.

the construction of SMRs:

> "*Key to construction certainty is minimisation of on site safety related work, regulatory oversight, change process and testing*".

4.2.2. Discussions

Relevant considerations can be drawn by the summary of the results in Fig. 4. The main elements hindering SMR construction can be categorised as follows.

- Financing

The 1st and 2nd ranked elements (i.e. perceived investment risk and availability of funds) are both related to SMR financing. Therefore, financing represents the main issue for SMR construction, according to the experts. A high perceived investment risk (volatility and value at risk) determines a lack of confidence in potential investors. However, according to Refs. [16], the "*less value at risk*" with respect to LRs should be a key advantage of SMRs, particularly for the FOAK where the money is "*gambled on a much smaller investment*". A reasonable hypothesis is that, although SMRs should be a less risky investment (in terms of value at risk) with respect to LRs, the lack of a FOAK (5th-ranked) and the lack of a supply chain (11th-ranked) enabling to harness the advantages of modularisation and modularity determine a high perceived investment risk.

- Economics

The 3rd and 4th ranked elements (i.e. availability of cheaper alternative technologies to generate electricity and wholesale price of electricity) are related to SMR economics and SMR competitiveness in the electricity market. Therefore, according to the experts, SMR could be uncompetitive with respect to other energy sources, and this represents a critical element hindering SMR construction.

- Technological readiness

The 5th, 10th, and 11th ranked elements (i.e. the lack of a FOAK, technology readiness and supply chain availability) are related to SMR technological readiness (and in a certain extent to SMR financing). This element is particularly relevant for SMR designs adopting "never commercially operated" technologies such as molten salt fuelled (and cooled) advanced reactor technologies [9]. On the contrary, the other elements of the "technological readiness" category can be reasonably generalised to all SMR designs. "Technological readiness" elements are characterised by a relatively long resolution time and are strongly influenced by the elements related to "policy and regulation".

- Policy and regulation readiness

The 6th and 7th ranked elements (i.e. political support, licensing and regulatory constraints) are related to SMR policy and regulation readiness (and to a certain extent to SMR financing). As discussed in Section 3.2, current licensing processes represent a key issue for SMRs for several reasons, including timing and cost. Political support in developing specific SMR licensing processes could be a solution to overcome these barriers and lower perceived investment risk by investors.

- Other critical elements: Public acceptability and uncertainty about the cost/benefit analysis

Another critical element hindering SMR construction is the "uncertainty about the cost-benefit analysis" (8th-ranked). As highlighted by Ref. [16], the methodologies for the cost-benefit analysis are often inadequate to deal with a nuclear programme, and there is either a classical cost-benefit analysis (infrastructure level) or an enhanced one (stakeholder level).

Another consideration regards the public acceptability (9th-ranked) of SMRs, which is a controversial point in the literature. According to Ref. [36,63], public acceptability of NPPs can be improved with SMRs for the following reasons: security improvement, environmental impact improvement, proliferation resistance improvement, passive safety system and massive deployment. On the contrary [46,64] consider the public acceptability of new concepts as one of the disadvantages of SMRs that must be overcome to develop SMRs in the near future. However, the role SMRs could have on the public acceptability is fundamental for the future of NPPs. Indeed, as highlighted by Ref. [36], Italy (all national plants decommissioned after a referendum) and Finland (where Olkiluoto inhabitants agreed on the construction of an NPP) are examples of the key role of the public. According to the experts, the public acceptability is among the "critical general elements" hindering SMR construction.

Governments should fund (directly or indirectly) a consistent amount for the FOAK SMR to reduce or eliminate the 2nd-ranked element hindering SMR construction (i.e. availability of funds). This would allow having a reference plant improving the confidence of the investors. This would also promote the development of a supply chain enabling the expected advantages of modularisation and modularity, and the definition of a strategy at national or international level. For instance, developing an SMR design and building the supply chain and the reactors in its own country aiming to export the technology [16] could make SMR investment more attractive with respect to other technologies. Vendors and suppliers should develop a supply chain enabling to achieve the expected advantages of modularisation and modularity in order to both reduce the "perceived investment risk" and to improve the overall SMR economic competitiveness.

4.3. SMR licensing and regulation

4.3.1. Results

Fig. 5 shows the ranking of the licensing and regulatory elements hindering the construction of SMRs, as perceived by the experts (see Appendix B for more details about the frequency of the responses).

Consistently with [17], licensing and regulatory elements with an MS higher than the average total value (3.27) can be defined as "critical licensing and regulatory elements" strongly hindering the construction of SMRs. Therefore, from 1st (timing of the licensing process) to the 4th (ownership and financial requirements associated with the operator of a nuclear power plant) ranked element can be considered "critical licensing and regulatory elements" to SMR construction.

One of the respondents commented explaining one of the reasons behind the long licensing process:

> "*In USA Part 52 regulation creates serial process […] results in long regulatory process*".

One of the experts stressed this point, commenting:

> "*the Regulatory process and its cost is more than can be recovered for plants less than 1,000MW in electrical output*".

Another expert focused on the 6th-ranked regulatory element (i.e. the limited experience and capability of the regulatory body) commenting:

> "*In the US, SMR licensing is limited to LWR designs because NRC has no technical or regulatory capacity to license next generation designs, even if safer or more efficient*".

Fig. 6 shows the ranking of the licensing and regulatory elements favouring SMR construction (Appendix C for more details about the frequency of the responses).

Licensing and regulatory elements with an MS higher than the average total value (3.51) can be defined as "critical licensing and regulatory elements" strongly favouring the construction of SMRs. Therefore, from the 1st (promote the early meetings with the regulatory body in order to reduce the licensing and regulatory risk) to the 6th (allow the in-factory certification) ranked element can be considered "critical licensing and regulatory elements" favouring SMR construction.

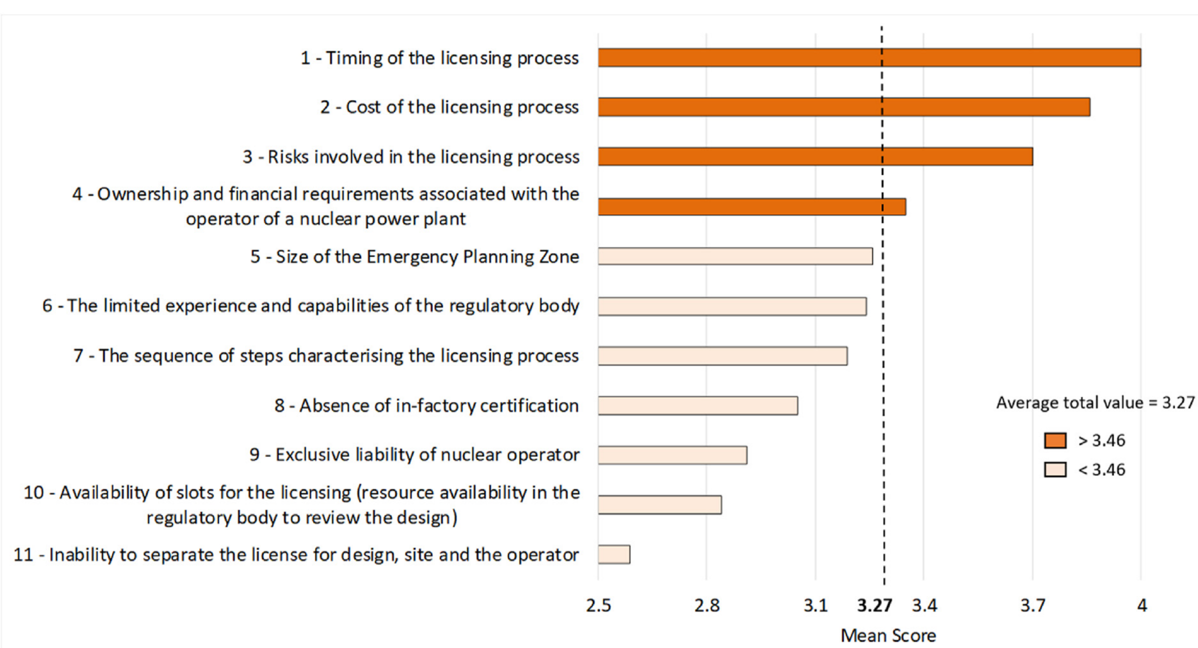

Fig. 5. Ranking of the licensing and regulatory elements hindering SMR construction.

4.3.2. Discussions

The uncertainty arising from the regulatory framework, and in particular the licensing process, is perceived as a critical barrier for the efficient and effective deployment of SMRs. The survey results in Figs. 5 and 6 show consistently and respectively the main licensing and regulatory elements hindering and favouring SMR construction, and can be categorised as follows.

- Time

Fig. 5 shows that the timing of the licensing process is the 1st-ranked element hindering SMR construction. The duration of the licensing process can severely harm the efficient installation of SMRs, limiting the envisaged advantages of modularisation. [13] argue that SMR licensing could be even longer than SMR construction because of several elements, such as the novelty of the technology, the different safety principle with respect to traditional LRs, the high number of institutions involved. Consistently, as shown in Fig. 6, the experts point out two key elements related to the timing of the licensing process favouring SMR construction: "Reduce the time of the licensing process before construction" (2nd-ranked) and "Reduce the time of the phases of the licensing process in parallel with the construction and commissioning of SMRs" (3rd-ranked).

- Cost

According to the experts, the costs associated with the licensing process (2nd-ranked in Fig. 5) is a relevant barrier for SMRs. Compared to LRs, SMRs cannot dilute this cost on large power output [29]. Furthermore, [29] highlights a cost for regulatory approval for SMRs higher than for LRs because of the newness of the SMR designs and the overall SMR concept. Consistently, as shown in Fig. 6, the experts point out that the reduction of the cost of the licensing process before construction (4th-ranked in Fig. 6) is a key element favouring SMR construction.

- Risk

According to Ref. [13,29], the SMR licensing process is less predictable than LRs determining investors perceive a relevant completion risk. This is confirmed by the results in Fig. 5, showing that, according to the experts, "the risk involved in the licensing process" (3rd-ranked) and the "ownership and financial requirements associated with the operator of an NPP" (4th-ranked) are two licensing and regulatory elements hindering SMR construction. This risk is particularly relevant for the FOAK reactors as there is limited experience in licensing SMRs. Moreover, traditional licensing processes have been developed for LRs, and there are some potential incompatibles with SMRs. These potential misalignments between SMRs planning and delivery and traditional licensing process can be particularly critical for nuclearised countries, with long-established laws and regulations. Some nuclearised countries are acting proactively to overcome these barriers of traditional licensing processes; for example, the UK is developing a policy promoting SMRs that include changes to the licensing process [65]. Conversely, newcomers' countries, can design their regulations and law to accommodate their nuclear programme, and potentially introduce bespoke licensing process and regulatory requirements for SMRs.

Consistently, as shown in Fig. 6, the experts point out that the promotion of the early meeting with the regulatory body in order to reduce the licensing and regulatory risk is a key element favouring SMR construction.

According to the authors, the survey results suggest that substantial changes in the licensing process are needed to favour SMR construction. There is space for improving the licensing processes, including reducing the licensing time and cost, fostering "early

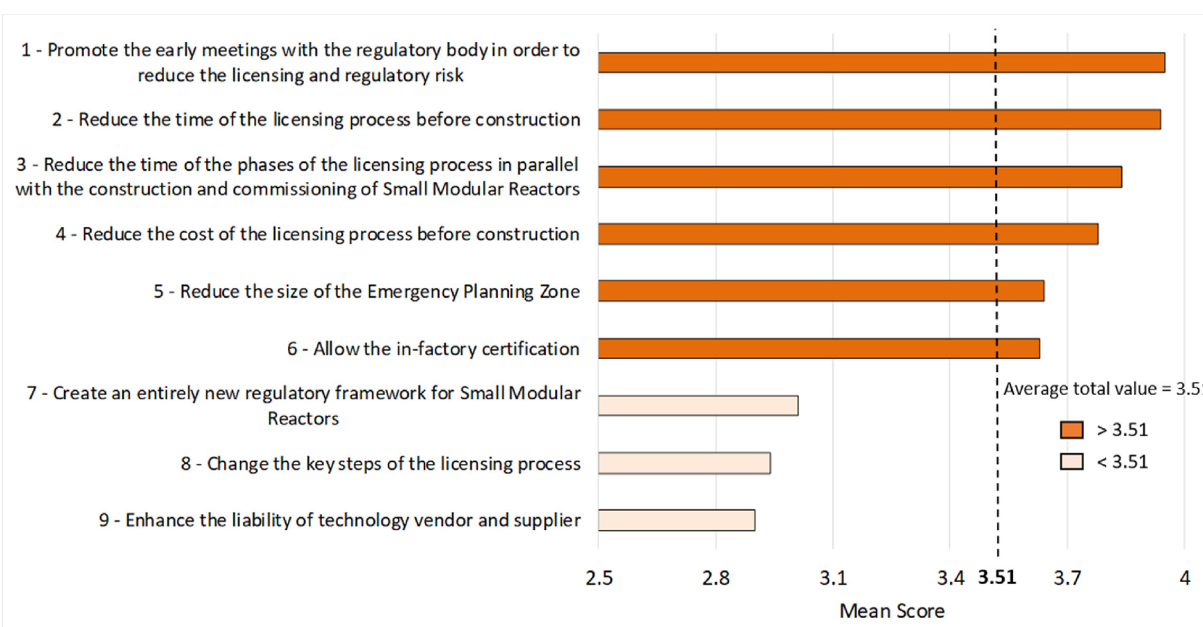

Fig. 6. Ranking of the licensing and regulatory elements favouring SMR construction.

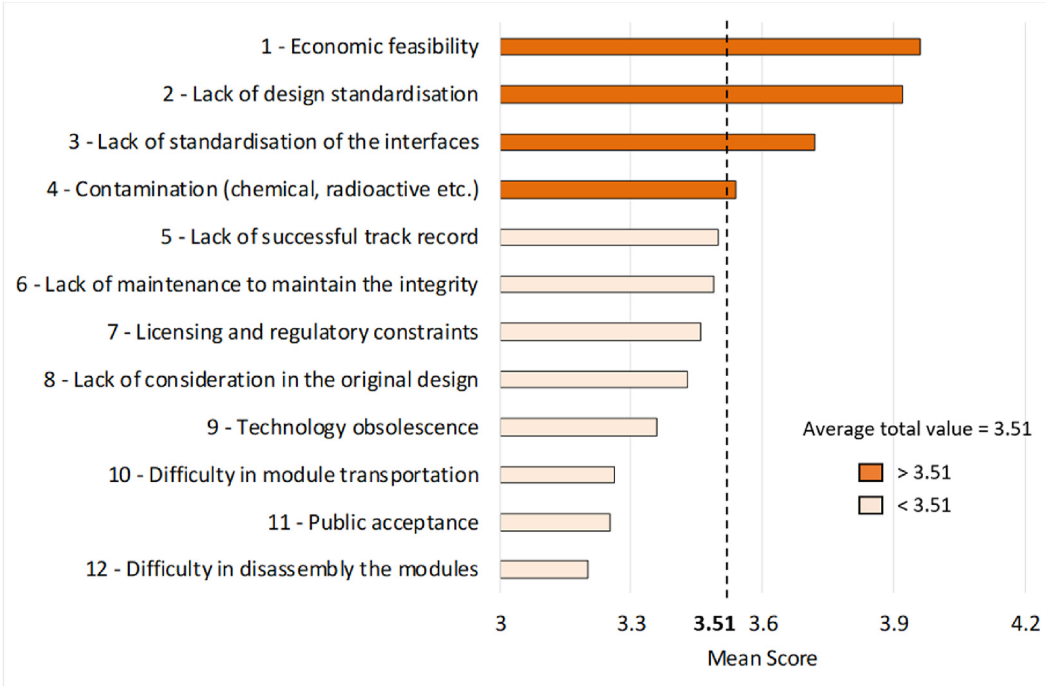

Fig. 7. Ranking of elements hindering the reuse of SMR modules.

meetings" with regulatory bodies in order to reduce the licensing and regulatory risk and enhancing manufacturing certifications (6th ranked in Fig. 6). The survey confirmed that these are some of the most effective measures to reduce the side-effects of licensing, and regulatory requirements, on the economics of SMRs.

4.4. SMR decommissioning: Linking modularisation and CE

4.4.1. Results

Fig. 7 shows the ranking of the elements hindering the reuse of SMR modules (see Appendix D for more details about the frequency of the responses).

Consistently with [17], elements with an MS higher than the average total value (3.51) can be defined as "critical elements" strongly hindering the reuse of SMR modules. Therefore, from the 1st (economic feasibility) to the 4th (contamination) ranked element can be considered "critical elements" strongly hindering the reuse of SMR modules.

One of the experts commented on the issue of standardisation:

"*Reactor modules will be very unique in most cases*".

Fig. 8 shows the ranking of elements favouring the reuse of SMR modules (see Appendix E for more details about the frequency of

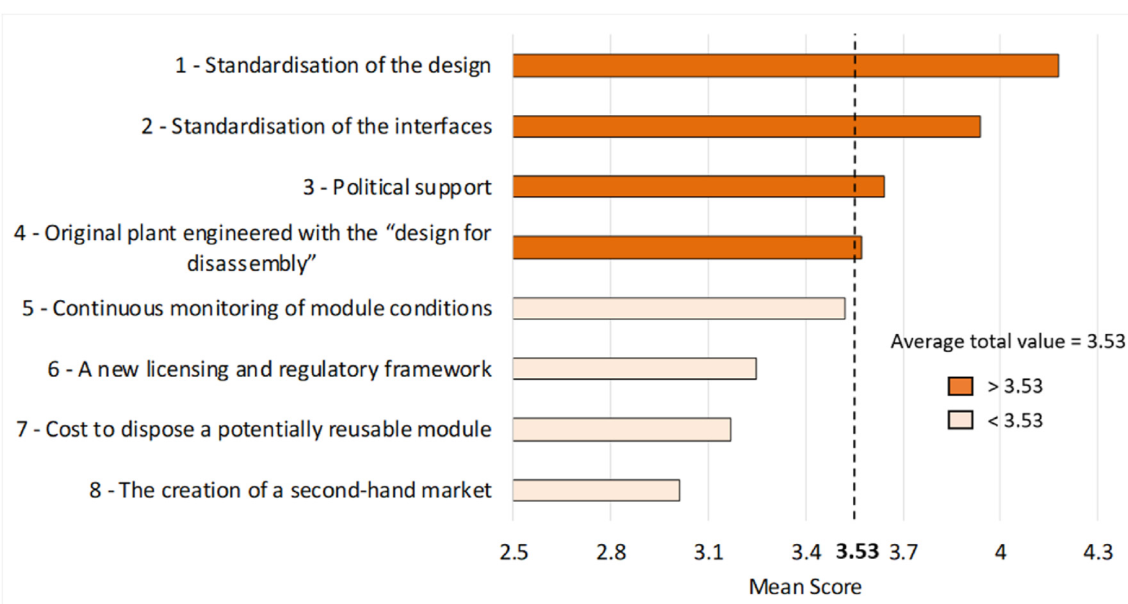

Fig. 8. Ranking of the elements favouring the reuse of SMR modules.

the responses).

Elements with an MS higher than the average total value (3.53) can be defined as "critical elements" strongly favouring the reuse of SMR modules. Therefore, from the 1st (standardisation of the design) to the 4th (original plant engineered with the "design for disassembly") ranked element can be considered "critical elements" favouring the reuse of SMR modules.

One of the experts commented:

"*I don't see this as a significant issue in the introduction and deployment of modular reactors at this stage of development*".

Another expert commented on the importance of regulatory acceptance and the issue of contamination:

"*The keys to reuse are (1) public and (2) regulatory acceptance and (3) rad con. Once the module is hot, there is no way it can be reused in the US in all likelihood*".

4.4.2. Discussions

Figs. 7 and 8 show consistently and respectively the main elements hindering and favouring the reuse of SMR modules, and can be categorised as follows.

- Economics

According to the experts, the main element (1st-ranked) hindering the reuse of SMR modules is the economic feasibility. [17] point out that the overall "Modular CE" strategy (i.e. "*the factory fabrication, transportation and installation on-site of modules aiming to facilitate the reuse/repair/replacement/recycling of modules/components/materials*") could add complexity both in terms of regulation and design phase of energy infrastructure, potentially leading to an increase in cost and schedule. Consistently, as shown in Fig. 8, the experts point out the political support (3rd-ranked) as a key element favouring the reuse of SMR modules. A reasonable hypothesis is that political support can balance the increase in cost and, therefore, favour the reuse of SMR modules and the overall SMR sustainability.

- Design

Fig. 7 shows that two key elements hindering the reuse of SMR modules are the "lack of design standardisation" (2nd-ranked) and "lack of standardisation of the interfaces" (3rd-ranked). Consistently, the experts point out, as shown in Fig. 8, "standardisation of the design" (1st-ranked) and "standardisation of the interfaces" (2nd-ranked) as the main elements favouring the reuse of SMR modules. In the general case of energy infrastructure, these two elements are pointed out as key challenges for the reuse of modules [15]. [15] highlight that, in general, the "complete standardisation" of energy infrastructure is unrealistic, at least in the short and middle term. This is also valid for the case of SMRs. However, as argued in the case of energy infrastructure [15], SMR "complete plant standardisation" is not essential. Indeed, the standardisation of SMR module interfaces might be already "*a giant leap forward in the right direction*". Furthermore, [15] highlight that Modular CE strategy in general and the reuse of SMR modules in particular need to be considered in the early design stages, including requirements such as "design for disassembly" [10,17]. In the building construction sector, [66–68] point out the key role of the design for deconstruction/disassembly to achieve the closed-loop material cycle, and recognise the merit of modularisation in fostering the building closed-loop material cycle. The need for a "design for disassembly" is confirmed by the survey results (4th-ranked in Fig. 8).

- Contamination

Another consideration regards the 4th-ranked item in Fig. 7, i.e. contamination (chemical, radioactive, etc.) of SMR modules. According to experts, contamination could limit the reuse of SMR modules. However, MS is much lower than the first three ranked items. According to Ref. [69], most of the components of an NPP do not become contaminated (or at a very low level). Therefore, a reasonable hypothesis is that contamination is a strong barrier for the reuse of SMR modules that become contaminated, but it could regard a relatively small percentage of SMR modules and components.

The results of the latest section of the survey can lead to a range of possible steps to improve SMR decommissioning leveraging modularisation. According to the authors, the most relevant are:

1) Further investigation of the "Modular CE" strategy. Further research is needed to evaluate the technical feasibility and related implications of Modular CE strategy over the life-cycle of SMRs. In particular, it is necessary to assess which modules/components could be reused and which could not. In the case of reusable modules and components, enabling factors (e.g. a second-hand market, standardisation of the interfaces) and challenges (e.g. increase in complexity, economic feasibility) should be considered. In general, further studies on SMR decommissioning through a "circular economy" lens are needed.

2) Policies fostering "Modular CE" strategy. In the case of techno-economic feasibility of Modular CE strategy, policymakers should provide policies fostering its implementation. As shown by Refs. [15] in the case of modular energy infrastructure, policymakers should develop policies fostering standard design and interfaces promoting the reuse of SMR modules across plants, and considering Modular CE implementation at different levels (i.e. country-level and internationally).

5. Conclusions

Driven by the interest in decarbonising the economy, there is a growing interest in SMRs. Despite several advantages over the large counterparts, the construction of SMRs has been minimal, and the reasons behind the slow adoption are unclear. This paper provides three main contributions.

The first contribution relates to the identification and ranking of the general elements hindering SMR construction. The results show that the elements hindering SMR construction are related to three main categories (in order of relevance): 1) Financing, 2) Economics, and 3) Readiness. The perceived investment risk (MS = 4.20), availability of funds (MS = 4.12), and the availability of cheaper alternative technologies to generate electricity (MS = 4.11) are the main elements hindering SMR construction.

The second contribution relates to the identification and ranking of specific licensing and regulatory elements affecting SMR construction. The results show that the timing of the licensing process (MS = 4.0), its cost (MS = 3.86) and the risk involved in the licensing process (MS = 3.7) are the main licensing and regulatory elements hindering SMR construction. On the contrary, the promotion of the early meetings with the regulatory body (MS = 3.95), the reduction of the licensing process time before construction (MS = 3.94), and the reduction of the time of the licensing process phases in parallel with the construction and commissioning of SMRs (MS = 3.84) are the main licensing and regulatory elements favouring SMR construction.

The third contribution relates to SMR decommissioning, i.e. the opportunity to reuse SMR modules. The results show that the elements affecting the reuse of SMR modules are related to two main categories: 1) Economics, and 2) Design. The economic feasibility (MS = 3.96), lack of design standardisation (MS = 3.92), and lack of standardisation of the interfaces (MS = 3.72) are the main elements hindering the reuse of SMR modules. On the contrary, standardisation of the design (MS = 4.18), standardisation of the interfaces (MS = 3.94), and political support (MS = 3.64) are the main elements favouring the reuse of SMR modules.

The results of this paper are meaningful for critical stakeholders (regulators, vendors/designers, policymakers, etc.) involved in the nuclear business, allowing to focus on a series of steps to favour the construction of SMRs and improve SMR life-cycle, including decommissioning. According to the authors (based on the results of the survey and their reflection and experience), the most relevant steps are: 1) Government support for the FOAK SMR and developing a supply chain 2) Amending the licensing process to reflect the nature of SMRs, 3) Further investigation of "Modular CE" strategy, including the development of appropriated policies.

Author statement

Benito Mignacca: Conceptualization, Methodology, Investigation, Formal Analysis, Resources, Writing-Original Draft, Visualization, Writing - Review & Editing, Visualization, Project Administration**. Giorgio Locatelli**: Conceptualization, Methodology, Resources, Writing-Original Draft, Writing - Review & Editing, Visualization, Supervision, Project Administration, Funding acquisition. **Tristano Sainati**: Conceptualization, Methodology, Writing-Original Draft, Writing - Review & Editing, Resources

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/N509681/1. Furthermore, this work was partially supported by the Major Project Association (MPA). The authors are especially grateful to Simon Marshall (Director of Independent Nuclear Expertise Limited) who provided insightful comments on a draft. The authors also acknowledge the substantial contribution of the reviewers. The opinions in this paper represent only the point of view of the authors, and only the authors are responsible for any omission or mistake. This paper should not be taken to represent in any way the point of view of MPA or EPSRC or any other organisation involved.

Appendix

Appendix A
Ranking of general elements hindering SMR construction

General elements hindering SMR construction	Frequency 1	2	3	4	5	Mean	SD	Rank
Perceived investment risk	1	6	14	28	48	4.20	0.97	1
Availability of funds	2	5	13	35	40	4.12	0.97	2
Availability of cheaper alternative technologies to generate electricity	4	5	16	23	49	4.11	1.11	3
Wholesale price of electricity	3	5	19	27	43	4.05	1.06	4
Lack of reference plant(s) (or lack of First-Of-A-Kind Unit)	2	10	14	27	44	4.04	1.09	5
Political support	3	11	23	26	32	3.77	1.13	6
Licensing and regulatory constraints	2	15	19	32	29	3.73	1.11	7
Uncertainty about the cost/benefit analysis	1	12	32	32	20	3.60	0.98	8
Public acceptability	3	17	25	22	29	3.59	1.18	9
Technology readiness	6	14	18	36	22	3.56	1.17	10
Supply chain availability	1	14	31	34	17	3.54	0.97	11
Lack of planning at programme/country level	4	16	29	28	20	3.45	1.11	12
Uncertainties about the Operation & Maintenance costs	5	17	35	26	14	3.28	1.07	13
Diseconomies of scale with respect to large reactors	9	21	31	22	14	3.11	1.17	14
Lack of experience in operations	13	23	24	26	10	2.97	1.21	15
Site availability	19	31	25	13	7	2.56	1.17	16
Uncertainties about end of life	22	32	30	10	3	2.38	1.04	17
Uncertainties about the decommissioning cost	23	41	21	9	3	2.26	1.02	18

Appendix B
Ranking of licensing and regulatory elements hindering SMR construction

Licensing end regulatory elements	Frequency 1	2	3	4	5	Mean	SD	Rank
Timing of the licensing process	0	9	14	37	32	4.00	0.94	1
Cost of the licensing process	2	11	20	24	35	3.86	1.12	2
Risks involved in the licensing process	0	9	32	27	23	3.7	0.95	3
Ownership and financial requirements associated with the operator of a nuclear power plant	5	16	25	34	12	3.35	1.08	4
Size of the Emergency Planning Zone	5	25	24	17	21	3.26	1.23	5
The limited experience and capabilities of the regulatory body	9	19	22	25	17	3.24	1.25	6
The sequence of steps characterising the licensing process	6	18	30	27	10	3.19	1.08	7
Absence of in-factory certification	8	21	29	26	8	3.05	1.10	8
Exclusive liability of nuclear operator	9	29	27	15	12	2.91	1.18	9
Availability of slots for the licensing (resource availability in the regulatory body to review the design)	10	35	19	16	12	2.84	1.22	10
Inability to separate the license for design, site and the operator	17	28	27	13	6	2.59	1.14	11

Appendix C
Ranking of licensing and regulatory elements favouring SMR construction

Licensing and regulatory elements	Frequency					Mean	SD	Rank
	1	2	3	4	5			
Promote the early meetings with the regulatory body in order to reduce the licensing and regulatory risk	5	6	13	28	36	3.95	1.16	1
Reduce the time of the licensing process before construction	3	7	14	33	32	3.94	1.06	2
Reduce the time of the phases of the licensing process in parallel with the construction and commissioning of Small Modular Reactors	4	8	13	36	27	3.84	1.1	3
Reduce the cost of the licensing process before construction	3	7	21	32	25	3.78	1.05	4
Reduce the size of the Emergency Planning Zone	7	9	20	25	27	3.64	1.24	5
Allow the in-factory certification	4	8	27	27	22	3.63	1.09	6
Create an entirely new regulatory framework for Small Modular Reactors	16	13	26	20	13	3.01	1.3	7
Change the key steps of the licensing process	12	21	23	16	12	2.94	1.26	8
Enhance the liability of technology vendor and supplier	7	24	35	17	6	2.9	1.02	9

Appendix D
Ranking of the elements hindering the reuse of SMR modules

Elements	Frequency					Mean	SD	Rank
	1	2	3	4	5			
Economic feasibility	0	9	16	24	31	3.96	1.02	1
Lack of design standardisation	2	7	12	31	26	3.92	1.03	2
Lack of standardisation of the interfaces	3	11	16	23	25	3.72	1.16	3
Contamination (chemical, radioactive etc.)	5	15	14	24	22	3.54	1.24	4
Lack of successful track record	5	10	23	24	18	3.50	1.15	5
Lack of maintenance to maintain the integrity	7	9	22	22	20	3.49	1.22	6
Licensing and regulatory constraints	5	14	16	29	16	3.46	1.17	7
Lack of consideration in the original design	5	10	27	20	17	3.43	1.14	8
Technology obsolescence	9	8	22	27	14	3.36	1.21	9
Difficulty in module transportation	5	17	20	28	10	3.26	1.12	10
Public acceptance	12	12	16	22	17	3.25	1.35	11
Difficulty in disassembly the modules	6	17	22	25	10	3.20	1.13	12

Appendix E
Ranking of the elements favouring the reuse of SMR modules

Elements	Frequency					Mean	SD	Rank
	1	2	3	4	5			
Standardisation of the design	2	6	5	33	38	4.18	0.99	1
Standardisation of the interfaces	2	10	11	29	32	3.94	1.09	2
Political support	5	11	16	25	24	3.64	1.21	3
Original plant engineered with the “design for disassembly”	1	15	24	23	21	3.57	1.08	4
Continuous monitoring of module conditions	3	11	25	29	16	3.52	1.05	5
A new licensing and regulatory framework	8	15	23	24	14	3.25	1.20	6
Cost to dispose a potentially reusable module	4	16	35	18	10	3.17	1.03	7
The creation of a second-hand market	8	22	23	23	8	3.01	1.14	8

References

[1] United Nations. About the sustainable development goals - united Nations sustainable development. Available from: https://www.un.org/sustainabledevelopment/sustainable-development-goals/; 2020.

[2] Gürel AE, Ağbulut Ü, Ergün A, Ceylan İ. Environmental and economic assessment of a low energy consumption household refrigerator. Eng Sci Technol an Int J 20;23.

[3] Petrol British. BP statistical review of world energy. 2019.

[4] Ağbulut Ü, Ayyıldız M, Sarıdemir S. Prediction of performance, combustion and emission characteristics for a CI engine at varying injection pressures. Energy 2020:197.

[5] Ağbulut Ü. Turkey's electricity generation problem and nuclear energy policy. Energy Sources, Part A Recover Util Environ Eff 2019;41(18):2281–98.

[6] Ağbulut Ü, Ceylan İ, Gürel AE, Ergün A. The history of greenhouse gas emissions and relation with the nuclear energy policy for Turkey. Int J Ambient Energy 2019:1–9.

[7] International Energy Agency. Global energy & CO2 status report. 2019.

[8] Locatelli G. Why are megaprojects, including nuclear power plants, delivered overbudget and late? Reasons and Remedies. Report MIT-ANP-TR-172. In: Center for advanced nuclear energy systems (CANES). Massachusetts Institute of Technology; 2018.

[9] IAEA. Advances in small modular reactor technology developments. 2018.

[10] IAEA. Small modular reactors (SMR). IAEA; 2020. Available from: https://www.iaea.org/topics/small-modular-reactors.

[11] IAEA. Status of Innovative small and Medium sized reactor designs 2005. Iaea-Tecdoc-1485; 2006.

[12] IAEA. PRIS - power reactor information system. Available from: https://pris.iaea.org/PRIS/home.aspx; 2020.

[13] Sainati T, Locatelli G, Brookes N. Small modular reactors: licensing constraints and the way forward, vol. 82. Energy; 2015. 1092–5.

[14] Mignacca B, Alaassar M, Locatelli G, Invernizzi DC. We never built small modular reactors (SMRs), but what do we know about modularization in construction?. In: International conference on nuclear engineering, proceedings, ICONE.; 2018.

[15] Mignacca B, Locatelli G, Velenturf A. Modularisation as enabler of circular economy in energy infrastructure. Energy Pol 2020;139:111371.

[16] Mignacca B, Locatelli G. Economics and finance of Small Modular Reactors: a systematic review and research agenda. Renew Sustain Energy Rev 2020;118.

[17] Mao C, Shen Q, Pan W, Ye K. Major barriers to off-site construction: the developer's perspective in China. J Manag Eng 2015;31(3):1–8.

[18] Proskurina S, Alakangas E, Heinimö J, Mikkilä M, Vakkilainen E. A survey analysis of the wood pellet industry in Finland: future perspectives. Energy 2017 Jan;118:692–704.

[19] Ropponen J, Lyytinen K. Components of software development risk: how to address them? A project manager survey. IEEE Trans Software Eng 2000;26(2):98–112.

[20] Chan DWM, Chan APC, Lam PTI, Wong JMW. An empirical survey of the motives and benefits of adopting guaranteed maximum price and target cost

contracts in construction. Int J Proj Manag 2011 Jul;29(5):577–90.
[21] Nunnallly JC. Psychometric theory. second ed. New York: McGraw-Hill; 1978.
[22] GIF/EMWG. Cost estimating guidelines for generation IV nuclear energy systems - revision 4.2. 2007.
[23] Boldon L, Sabharwall P, Painter C, Liu L. An overview of small modular reactors: status of global development, potential design advantages, and methods for economic assessment. Int J Energy Environ Econ 2014;22(5):437–59.
[24] Maronati G, Petrovic B, Wyk JJ Van, Kelley MH, White CC. EVAL: a methodological approach to identify NPP total capital investment cost drivers and sensitivities. Prog Nucl Energy 2017;104:190–202.
[25] Carelli MD, Ingersoll DT. Handbook of small modular nuclear reactors. Woodhead Publishing, Elsevier; 2014. p. 1–536.
[26] Maronati Petrovic B, Banner JW, White CC, Kelley MH, Van Wyk J. Total capital investment cost evaluation of smr modular construction designs. In: International congress on advances in nuclear power plants. San Francisco, California, USA: ICAPP 2016; 2016. p. 943–8.
[27] Maronati G, Petrovic B. Extending modularization from modules to super modules: a cost evaluation of barge-Transportable small modular reactors Petrovic. In: International congress on advances in nuclear power plants. Charlotte, NC, USA: ICAPP 2018; 2018. p. 357–62.
[28] Lloyd CA, Roulstone ARM, Middleton C. The impact of modularisation strategies on small modular reactor cost. In: International congress on advances in nuclear power plants 2010. NC, USA: ICAPP 2018. Charlotte; 2018.
[29] UxC Consulting. SMR Market Outlook. 2013;30076(770).
[30] Mignacca B, Alawneh AH, Locatelli G. Transportation of small modular reactor modules: what do the experts say?. In: International conference on nuclear engineering, proceedings, ICONE; 2019.
[31] Locatelli G, Bingham C, Mancini M. Small modular reactors: a comprehensive overview of their economics and strategic aspects. Prog Nucl Energy 2014;73:75–85.
[32] Boarin S, Ricotti ME. An evaluation of SMR economic attractiveness. Sci Technol Nucl Install 2014;2014:1–8.
[33] Small EY. Modular reactors - can building nuclear power become more cost-effective?. 2016.
[34] Locatelli G, Fiordaliso A, Boarin S, Ricotti ME. Cogeneration: an option to facilitate load following in Small Modular Reactors. Progress in nuclear energy, vol. 97. Elsevier Ltd; 2017. p. 153–61.
[35] Locatelli G, Boarin S, Fiordaliso A, Ricotti ME. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: a techno-economic analysis. Energy 2018;148:494–505.
[36] Mancini M, Locatelli G, Tammaro S. Impact of the external factors in the nuclear field: a comparison between small medium reactors vs. large reactors. In: 17th international conference on nuclear engineering. ICONE17. Brussels, Belgium; 2009.
[37] Locatelli G, Mancini M. The role of the reactor size for an investment in the nuclear sector: an evaluation of not-financial parameters. Prog Nucl Energy 2011;53(2):212–22.
[38] Iaea. Managing the financial risk associated with the financing of new nuclear power plant projects. 2017.
[39] Ramana MV, Agyapong P. Thinking big? Ghana, small reactors, and nuclear power. Energy Res Soc Sci 2016;21:101–13.
[40] Ramana MV, Ahmad A. Wishful thinking and real problems: small modular reactors, planning constraints, and nuclear power in Jordan. Energy Pol 2016;93:236–45.
[41] Cooper M. Small modular reactors and the future of nuclear power in the United States. Energy Res Soc Sci 2014;3(C):161–77.
[42] Ramana MV, Mian Z. One size doesn't fit all: social priorities and technical conflicts for small modular reactors. Energy Res Soc Sci 2014;2:115–24.
[43] Trianni A, Locatelli G, Trucco P. Competitiveness of small-medium reactors: a probabilistic study on the economy of scale factor. In: International congress on advances in nuclear power plants 2009. Tokyo, Japan: ICAPP 2009; 2009.
[44] Carelli MD, Mycoff CW, Garrone P, Locatelli G, Mancini M, Ricotti ME, et al. Competitiveness of small-medium, new generation reactors: a comparative study on capital and O&M costs. In: 16th international conference on nuclear engineering, ICONE16. Orlando, Florida, USA: ASME; 2008.
[45] Lokhov A, Cameron R, Sozoniuk V. OECD/NEA study on the economics and market of small reactors. ICAPP 2013. In: International congress on advances in nuclear power plants. Korea: Jeju Island; 2013.
[46] Vuji J, Bergmann RM, Skoda R, Mileti M. Small modular reactors: simpler, safer, cheaper? Energy 2012;45:288–95.
[47] Choi S, Jun E, Hwang I, Starz A, Mazour T, Chang S, et al. Fourteen lessons learned from the successful nuclear power program of the Republic of Korea. Energy Pol 2009 Dec;37(12):5494–508.
[48] World Nuclear Association. Nuclear power in the USA. 2019.
[49] Boarin S, Locatelli G, Mancini M, Ricotti ME. Financial case studies on small- and medium-size modular reactors. Nucl Technol 2012;178(2):218–32.
[50] IAEA. Handbook on nuclear law: implementing legislation. 2010.
[51] Licensing IAEA. Process for nuclear installation. Vienna: SSG-12; 2010.
[52] Iaea. Licensing the first nuclear power plant. Vienna: INSAG-26; 2012.
[53] IAEA. Independence in regulatory decision making. Vienna: INSAG-17; 2003.
[54] IAEA. Regulatory control of nuclear power plants Part A (Textbook). 2002.
[55] Sainati T, Locatelli G, Smith N. Project financing in nuclear new build, why not? The legal and regulatory barriers. Energy Pol 2019;129(May 2018):111–9.
[56] Ramana MV, BerzakHopkins L, Glaser A. Licensing small modular reactors. Energy 2013;61.
[57] Spengler MB. Federal - state Cooperation in nuclear power plant licensing. 1980.
[58] Invernizzi DC, Locatelli G, Brookes NJ. How benchmarking can support the selection, planning and delivery of nuclear decommissioning projects. Prog Nucl Energy 2017;99:155–64.
[59] Invernizzi DC, Locatelli G, Brookes NJ. Managing social challenges in the nuclear decommissioning industry: a responsible approach towards better performance. Int J Proj Manag 2017;35.
[60] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 2017;127:221–32.
[61] Preston F, Lehne J. A Wider Circle? The circular economy in developing countries A Wider Ci. 2017.
[62] United Nations. Transforming our world: the 2030 agenda for sustainable development. 2015.
[63] OECD/NEA. Small modular reactors: nuclear energy market potential for near-term deployment. 2016.
[64] Canadian nuclear Laboratories. Perspectives on Canada'S smr opportunity. 2017.
[65] EFWG. Market framework for financing small nuclear. 2018.
[66] Lehmann S. Resource recovery and materials flow in the city: zero waste and sustainable consumption as paradigms in urban development. Sustain Dev Law Policy 2011;11(1).
[67] Pulaski BM, Hewitt C, Horman M, Guy B. Design for deconstruction. Mod Steel Construct 2004;44:33–7.
[68] Lehmann S. Optimizing urban material flows and waste streams in urban development through principles of zero waste and sustainable consumption. Sustainability 2011:155–83.
[69] IAEA. Nuclear Decommissioning: Decommission nuclear facilities. 2020. Available from: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.